# Information Management in the Building Life Cycle – The Emerging Role of Digital Building Passports

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# Kurzfassung

Die strukturierte Verwaltung gebäudebezogener Daten ist entscheidend für fundierte Entscheidungen, Transparenz und nachhaltiges Wirtschaften über den gesamten Lebenszyklus von Gebäuden. Lebenszyklusorientierte Gebäudeinformationssysteme sollen diese Daten zentral bündeln und verschiedenen Akteuren zugänglich machen. Bislang fehlen jedoch klare Spezifikationen hinsichtlich ihrer Funktionalität, Inhalte und Abgrenzung.

Diese Arbeit schließt diese Lücke, indem sie systematisch definiert, welche Anforderungen ein lebenszyklusorientiertes Gebäudeinformationssystem erfüllen muss. Grundlage ist eine umfassende Analyse des Informationsbedarfs im Immobilienmanagement sowie der technologischen Potenziale für das Management gebäudebezogener Daten. Auf Basis eines entwickelten Anforderungsprofils wird ermittelt, dass digitale Gebäudepässe das größte Potenzial haben, diese Rolle einzunehmen, und sich dabei deutlich von spezifischeren Systemen abgrenzen.

Die grundlegende Idee von Gebäudepässen besteht bereits seit Jahrzehnten, ihre Entwicklung und Nutzung blieben jedoch lange Zeit begrenzt. Gründe hierfür liegen unter anderem in der mangelnden Spezifikation und Vereinheitlichung ihrer Funktionen. Dies führt zu Verwechslungen mit anderen Arten von Pässen, wie etwa Material- oder Renovierungspässen, oder mit BIM-Anwendungen. Bestehende Ansätze sind häufig fragmentiert und adressieren nur Teilaspekte. Mit den Fortschritten in der Digitalisierung und Automatisierung des Informationsmanagements gewinnen Gebäudepässe jedoch zunehmend an Bedeutung.

Auf Grundlage der Analyseergebnisse wird eine Informationssystemarchitektur entwickelt, die ein Framework für die zentralen Elemente eines digitalen Gebäudepasses und deren Interaktionen präzisiert. Dafür werden Modelle für relevante Funktionen, Daten, Nutzer, Technologien und Prozesse erarbeitet. Dies ermöglicht eine ganzheitliche Sicht auf das System und liefert zielgerichtete Hinweise zu dessen Entwicklung und Nutzung.

Die methodische Vorgehensweise kombiniert eine systematische Literaturrecherche, Modellierungstechniken zur Framework-Entwicklung sowie Expertenbefragungen zur Validierung und Schärfung zentraler Ergebnisse. Im Unterschied zu bisherigen Ansätzen geht die Arbeit über eine rein immobilienwirtschaftliche Perspektive hinaus, indem sie Konzepte der Wirtschaftsinformatik gezielt einbezieht.

Neben einer wissenschaftlichen Fundierung bietet die Arbeit wirtschaftliche und technische Empfehlungen für die Implementierung digitaler Gebäudepässe. Sie richtet sich an potenzielle Entwickler, Nutzer sowie Institutionen, die sich mit der Standardisierung solcher Systeme befassen. Damit liefert sie eine umfassende Grundlage für die Weiterentwicklung bestehender Systeme und die Nutzung technologischer Potenziale in der Immobilienwirtschaft.

# Abstract


The structured management of building-related data is essential for informed decision-making, transparency, and sustainable practices throughout the entire life cycle of buildings. Life cycle building information systems are intended to consolidate these data centrally and make them accessible to various actors. However, clear specifications regarding their functionality, content, and scope remain lacking.

This thesis addresses this gap by systematically defining the requirements that a life cycle building information system must fulfill. To this end, it presents a comprehensive analysis of the information needs in real estate management as well as the technological potential for managing building-related data. The findings are integrated into a requirement profile, which serves as the basis for assessing existing approaches. Digital building passports are identified as the most promising concept to fulfill this role, distinguishing themselves from more narrowly defined systems.

While the basic idea of building passports has existed for decades, their development and use have long remained limited. This is due, among other factors, to a lack of specification and standardization of their functions. As a result, they are often confused with other types of passports, such as material or renovation passports, or with Building Information Modeling (BIM) applications. Existing approaches are fragmented and frequently address only isolated aspects. With ongoing advances in the digitization and automation of information management, however, building passports are now gaining renewed relevance.

Based on the analytical findings, this thesis develops an information system architecture that provides a framework for the key elements of a digital building passport and their interactions. This includes conceptual models for essential functions, data, users, technologies, and processes. The result is a comprehensive system view that offers targeted guidance for both the development and use of such systems.

The methodological approach combines a systematic literature review, modeling techniques for framework development, and expert interviews to validate and refine key results. In contrast to previous efforts, this thesis moves beyond a purely real estate-centric perspective by deliberately incorporating concepts from information systems research.

In addition to its academic contribution, the thesis provides practical economic and technical recommendations for implementing digital building passports. It addresses developers, users, and institutions involved in the standardization of such systems. As such, it offers a solid foundation for advancing existing systems and leveraging technological potential in the real estate industry.

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# Abbreviations

| | |
|---|---|
| ACT | Advanced construction technology |
| AEC | Architecture, engineering, and construction |
| AECO | Architecture, engineering, construction, and operations |
| AECOO | Architecture, engineering, construction, operations, and owner |
| AI | Artificial intelligence |
| API | Application programming interface |
| ARIS | Architecture of integrated information systems |
| BFR | Baufachliche Richtlinien |
| BIA | Business intelligence and analytics |
| BIM | Building Information Modeling |
| BIS | Building information system |
| BMC | Business Model Canvas |
| BPMN | Business Process Modeling Notation |
| BRP | Building renovation passport |
| BSDD | buildingSmart Data Dictionary |
| CREM | Corporate real estate management |
| CSRD | Corporate Sustainability Reporting Directive |
| DBL | Digital Building Logbook |
| DBP | Digital Building Passport |
| DNSH | Do not significant harm |
| EC | European commission |
| eEPC | Enhanced Event-driven Process Chain |
| EPC | Energy Performance Certificate |
| ERM | Entity relationship model |
| ERMon | Adjustment monitoring |
| ESG | Environmental, social, and governance |
| ESRS | European Sustainability Reporting Standards |
| EU ETS | European Union Emission Trading Scheme |
| GHG | Greenhouse gas emissions |
| GRESB | Global Real Estate Sustainability Benchmark |
| GWP | Global warming potential |
| HOAI | Honorarordnung für Architekten und Ingenieure |
| IAM | Identity and Access Management |
| ICT | Information and communication(s) technology |
| IFC | Industry Foundation Classes |
| IoT | Internet of Things |
| ISA | Information system architecture |

| | |
|---|---|
| iSFP | Individueller Sanierungsfahrplan |
| KPI | Key performance indicators |
| LCA | Life Cycle Assessment |
| LC-BIS | Life cycle building information system |
| LZMon | Long-term monitoring |
| NFRD | Non-Financial Reporting Directive |
| PAI | Principal Adverse Impact |
| PREM | Public real estate management |
| RDF | Resources Description Framework |
| RFID | Radio Frequency Identification |
| SDG | Sustainable Development goals |
| SFDR | Sustainable Finance Disclosure Regulation |
| TMon | Technical monitoring |
| TSC | Technical screening criteria |
| UML | Unified Modeling Language |
| URI | Unique resource identifier |
| VOB | Vergabe- und Vertragsordnung für Bauleistungen |
| WSN | Wireless Sensor Network |
| XML | Extensible Markup Language |
| XSD | XML Schema Definition |

# I Introduction and basics

# 1 Introduction

*This chapter introduces the topic of the thesis by first outlining current drivers and trends in building-related information management (section 1.1). Building on this context, observable problems are described (section 1.2) and used to derive the research questions in order to define the underlying research gap (section 1.3). The chapter concludes with an overview of the structure of the thesis and how the research questions are addressed throughout the subsequent chapters (section 1.4).*

## 1.1 Drivers and trends in building-related information management

The real estate industry is undergoing significant change driven by megatrends. Defined as long-term, global, and profound developments, megatrends shape both the needs and behaviors of building users and the ways in which actors develop, construct, and operate buildings (Peyinghaus et al., 2022, p. 1). Due to the complexity of real estate as an asset and the variety of motives, needs, and tasks throughout the value chain, the industry is particularly susceptible to the effects of megatrends such as digitalization, sustainability, globalization, urbanization, and demographic change.

Among these developments, digitalization plays a particularly prominent role. More than any other trend, it creates both pressure to adapt and new opportunities for innovation. A review of articles on megatrends in the real estate industry found that digitalization was associated with the most positive expectations (Plößl & Just, 2020, p. 45). Its effects can be described through three main levers: the digitization of data, processes, and buildings (Peyinghaus et al., 2022, p. 9). These aspects are closely interconnected and supported by emerging technologies that enable the collection, storage, sharing, and analysis of building-related data, often within specialized information systems. These developments aim to enhance the data foundation, support decision-making, increase transparency, and reduce risks. In addition, the digitization of data and processes enables task automation, reduces complexity, and lowers the manual workload for involved actors.

Prominent trends and technologies driving this development include the following:

- Virtual building models: Digitally managing buildings through models, primarily using Building Information Modeling (BIM).
- Real-time data collection and AI-driven analysis: Leveraging sensor technologies to gather data and employing Artificial Intelligence (AI) methods to process and analyze this information.
- Interoperable information systems: Establishing systems to securely store and share building-related data across their life cycles, including concepts such as building passports and digital building logbooks.

- Digital platforms and ecosystems: Enabling data sharing and joint value creation among actors across the building life cycle.

At the same time, actors in the real estate industry increasingly recognize building-related data, in combination with technological advancements, as a critical resource for maintaining competitiveness and implementing more sustainable practices. Such data provide the foundation for describing the past, present, and future states of buildings and their related processes. They cover economic, environmental, social, technical, and other relevant dimensions. A well-structured and comprehensive approach to information management throughout the building life cycle is expected to increase productivity through cost savings, higher revenues, and additional intangible benefits, ultimately contributing to higher-quality and more sustainable buildings (KPMG, 2021, p. 4).

Key drivers behind the growing demand for building-related data include the following:

- Market dynamics and competitive pressure, which lead to a need for more efficient and optimized building operations.
- Increasing technization of buildings, introducing greater complexity and generating larger volumes of data.
- The rising importance of sustainability assessment and compliance, which requires detailed information to support decisions and meet regulatory and market expectations.
- New obligations for sustainability reporting, which mandate the collection and provision of extensive sustainability-related metrics.
- The integration of sustainability into various domains such as risk management, property valuation, financing, and marketing.
- Increasing stakeholder demands for transparency, which lead to a broader range of data requests across different communication channels.

A notable development at the intersection of information management and technological innovation is the emergence of information systems that facilitate more effective data management for individual buildings. However, these advancements also bring to light persistent challenges, many of which are rooted in longstanding issues of building-related information management. These challenges will be explored in the following section.

## 1.2 Problem definition

Historically, the real estate industry has struggled with an extremely heterogeneous and, in many cases, insufficient data foundation. Loss, obsolescence, modification, or the complete absence of data has often led to significant uncertainties about the true state of buildings and processes. This issue arises from various factors, with the heterogeneity and longevity of buildings and the diverse interests of owners and other actors throughout the life cycle being primary contributors. A key consequence has been the prevalence of information problems and asymmetries between actors. Building-related data are often not adequately shared across the life cycle, resulting in a lack of transparency, increased uncertainty, and higher costs for data collection (Rohde et al., 2011,

p. 14). Consequently, the full potential for transforming the building stock into a more sustainable resource remains largely untapped.

Despite broader megatrends, the real estate industry continues to face significant challenges in information management. Digitalization and the growing demand for sustainability have led to new approaches, but these frequently emerge as fragmented responses to specific problems. Solutions are often developed in parallel by different actors, leading to a “take-one-at-a-time” approach, in which innovations are introduced independently without unlocking their full potential through integration (Sawhney & Odeh, 2020, p. 46). This fragmented mindset has contributed to what scholars have described as "islands of automation", disconnected, department- or project-specific solutions that lack interoperability and hinder systemic digital transformation (Borrmann, Beetz, et al., 2018, p. 82). As a result, even innovative efforts often fail to create broader synergies or long-term value.

Unlike in other industries and academic domains, where the potential of digitalization is often celebrated, not all actors in the real estate industry view this development positively. Hesitation often stems from negative biases and past experiences with new technologies. This skepticism extends beyond tools and aids to the very design, construction, and operation of buildings. In the context of sustainability goals and cost-related factors, low-tech solutions have regained popularity, prompting discussions about the extent to which technization is genuinely helpful and beneficial. These considerations often go beyond the theoretical advantages of specific solutions, focusing instead on their practical feasibility for different actors within the industry (T. Auer et al., 2024, pp. 4–5).

Information systems face similar challenges. Professional real estate companies, for instance, have vastly different requirements than private homeowners, meaning even the most advanced tools may fail to deliver value if not appropriately implemented. While this diversity might suggest the need for actor-specific decision support, many actors still share common challenges related to data access, quality, and integration. These shared needs are rooted in the nature of buildings themselves, which, despite their unique characteristics, often follow similar principles across cases.

One approach to improving the data foundation and enhancing transparency is to aggregate and make building-related data available collectively in a single location. This concept underpins tools such as building passports, digital building logbooks, and housing files. Although these tools have been discussed for decades, they are now experiencing a resurgence in interest due to advances in digitalization and heightened requirements for information management. Pivotal initiatives, such as those by the European Commission (2020) and the Global Alliance for Buildings and Construction (GABC) (Hartenberger et al., 2021), have already proposed how a new generation of these tools could function.

However, several challenges hinder the broader adoption of such concepts. A major issue is the lack of consensus and clarity regarding their functionality, partly due to the absence of a standardized terminology. Different terms, such as "building passports" and "digital building logbooks," are sometimes used interchangeably to refer to the same concept, while similar terms, such as "building resource passport," may refer to tools with entirely different functions. This lack of standardization has contributed to the limited adoption of these tools. Other challenges include unclear data governance, high implementation costs, insufficient data quality, inconsistencies regarding scope and purpose, and a lack of interoperability with other tools (Carbonari et al., 2020, p. 16; Dourlens-Quaranta et al., 2020, p. 9; European Commission [EC], 2023, pp. 27–29).

Efforts to enhance transparency in the real estate industry often falter due to dynamically evolving framework conditions. Novel approaches to life cycle management of building-related data offer promising solutions. However, the growing volume of relevant data, driven by stricter climate and environmental protection requirements, new technical possibilities, and diverse economic interests, underscores the complexity of developing universally applicable approaches. To date, no widely adopted solutions have fully met the requirements for a sustainable, comprehensive concept that balances the interests and use cases of all actors.

## 1.3 Research questions

The problems identified reveal several substantial questions that will be posed in a structured order to clearly specify the research gap this thesis is going to address.

(1) What requirements must a system meet to function as a Life Cycle Building Information System (LC-BIS), considering building-related data needs, information management challenges, and digital solutions?
   a. What are the key categories of building-related data, and which data points are frequently required throughout the building life cycle?
   b. What are the main challenges in information management that hinder the fulfillment of data needs in the real estate industry, and how can LC-BISs address these challenges?
   c. How can digitization and automation based on information and communication technologies (ICT) support LC-BIS functions, and what specific requirements can be derived for their implementation?

Answering this question establishes a fundamental understanding of information management across the building life cycle. It connects task-oriented data needs with solution-oriented ICT capabilities by identifying key challenges and deriving requirements for a LC-BIS. This analysis serves as a conceptual bridge, integrating real-world information demands with digital solutions to define a comprehensive requirement profile.

(2) Which types of Building Information Systems (BISs) play a role in managing building-related information in theory and practice, and to what extent do they fulfill the requirements of a LC-BIS?
   a. What are the primary use cases and functional scopes of existing BISs?
   b. To what extent do these BISs cover the building life cycle, fulfill data needs, and meet the functional requirements of a LC-BIS? What are their key limitations?

Building on the first question, this research step examines existing BISs to assess their ability to meet LC-BIS requirements. The analysis reveals strengths, limitations, and gaps, providing a critical perspective on how well current systems support life cycle information management. This evaluation helps position LC-BISs within the broader ecosystem of building-related information systems, highlighting the need for further development or integration.

(3) How can a common framework be designed to meet the information management requirements of LC-BISs, and how can it support their practical development and implementation?
   a. Which core elements should a LC-BIS framework include to meet essential requirements?
   b. How should these core elements interact internally and externally to ensure effective system functionality?
   c. How can the framework facilitate the development, adoption, and practical implementation of LC-BISs? What are the key potentials, challenges, and strategies for success?

This question frames the overall proposals and results of the thesis by synthesizing insights from the previous analyses. It defines how a LC-BIS should be structured and implemented, ensuring that it meets information management requirements effectively. By establishing a common framework, this step provides a structured foundation for guiding the development, adoption, and real-world application of LC-BISs. Additionally, it addresses key challenges and strategies to facilitate implementation, ensuring the framework is both comprehensive and actionable.

By answering these questions, the aim is pursued to address a specific research gap within this thesis: Overcoming the insufficiencies of existing approaches to specify the functionality of a life cycle building information system and, even more important, lay the groundwork for its future success by systematically analyzing the needs of information management and pairing that with the potentials of digitalization. Since the topic has lots of different influences in a dynamically changing field, one aim of the thesis is to consolidate the existing knowledge. This requires the evaluation of key fundamentals of building-related information management which have not been dealt with in other works so far.

The outcomes of this thesis are addressed at several actor groups including:

- Researchers: The thesis is addressing a relevant gap in research in the context of the built environment. The aim is to provide a good foundation for other researchers who deal with the topic or specific aspects of it.
- Practitioners: Several outcomes of this thesis are to benefit practitioners from the real estate industry including initiators of life cycle building information systems and users. Based on the projected broad functionality of such a system, this will include building owners, real estate managers, and all kinds of other stakeholders throughout the building life cycle
- Regulators: Based on the severe interest of the public sector, this thesis can provide substantial insight for this group of actors by specifying the functionality of such a system. This lays the groundwork for the public sector to define its role in the fostering and implementing of such systems and whether they can serve as policy instruments in the future.

By addressing these actor groups this thesis shows relevance across theory and practice.

## 1.4 Approach and structure

This thesis is structured into four main parts:

- Part I encompasses the introduction and foundational concepts.
- Part II represents the core analytical section of the thesis.
- Part III includes the results and proposals derived from the analysis, as well as discussions of the ideas presented and the conclusion.
- Part IV contains appendices that support the comprehension of the main content by providing contextual information, documentation of analyses, and additional fundamentals on specific topics.

Following this introduction in chapter 1, chapter 2 provides a concise overview of relevant foundational concepts, drawing on pertinent literature. Topics are addressed systematically to clarify key terms, definitions, and concepts. This chapter covers real estate management basics, sustainability matters, fundamentals of information management grounded in business informatics, targeted aspects of information modeling, and a review of the current state of knowledge on information systems for real estate management.

Part II begins with chapter 3, which offers an in-depth analysis of information management aspects in the real estate industry. This chapter focuses on the building-related data needs of actors and tasks in real estate management and examines the practical challenges hindering data availability and sharing. A crucial intermediary result covers a taxonomy of building-related data needs.

Chapter 4 investigates the potential of ICTs for building-related information management, particularly within the context of BISs. The analysis addresses key processes and aspects of information management comprehensively.

The findings from chapters 3 and 4, alongside the foundational concepts introduced in chapter 2, form the basis for chapter 5, which specifies a requirement profile for LC-BISs. This requirement profile is then used to systematically review existing BISs in the real estate industry, evaluating the extent to which current systems meet these requirements in chapter 6. The analysis incorporates a systematic review of the literature.

Part III begins with chapter 7, which proposes an information system architecture (ISA) that defines the main elements of a digital building passport (DBP) functioning as a LC-BIS. This chapter conceptualizes the overall functionality of such a system holistically, partly utilizing modeling approaches.

Chapter 8 explores the feasibility and implementation possibilities of DBPs, building on the conceptual proposals presented in chapter 7 and supported by expert interviews. It examines potential barriers and challenges and offers practical implementation recommendations tailored to the thesis's target audience. Finally, the thesis concludes with chapter 9.

Part IV, the appendix, follows the structure of the thesis chapters and is organized into sections labeled A, B, C, etc. It provides supplementary information that, while not essential for maintaining the logical flow of the main text, remains relevant to the overall topic. These materials support the aim of establishing a solid foundation for future developments in the field. References within the text are formatted as “section A.1,” for example.

The detailed structure of the thesis is illustrated in Figure 1.1.

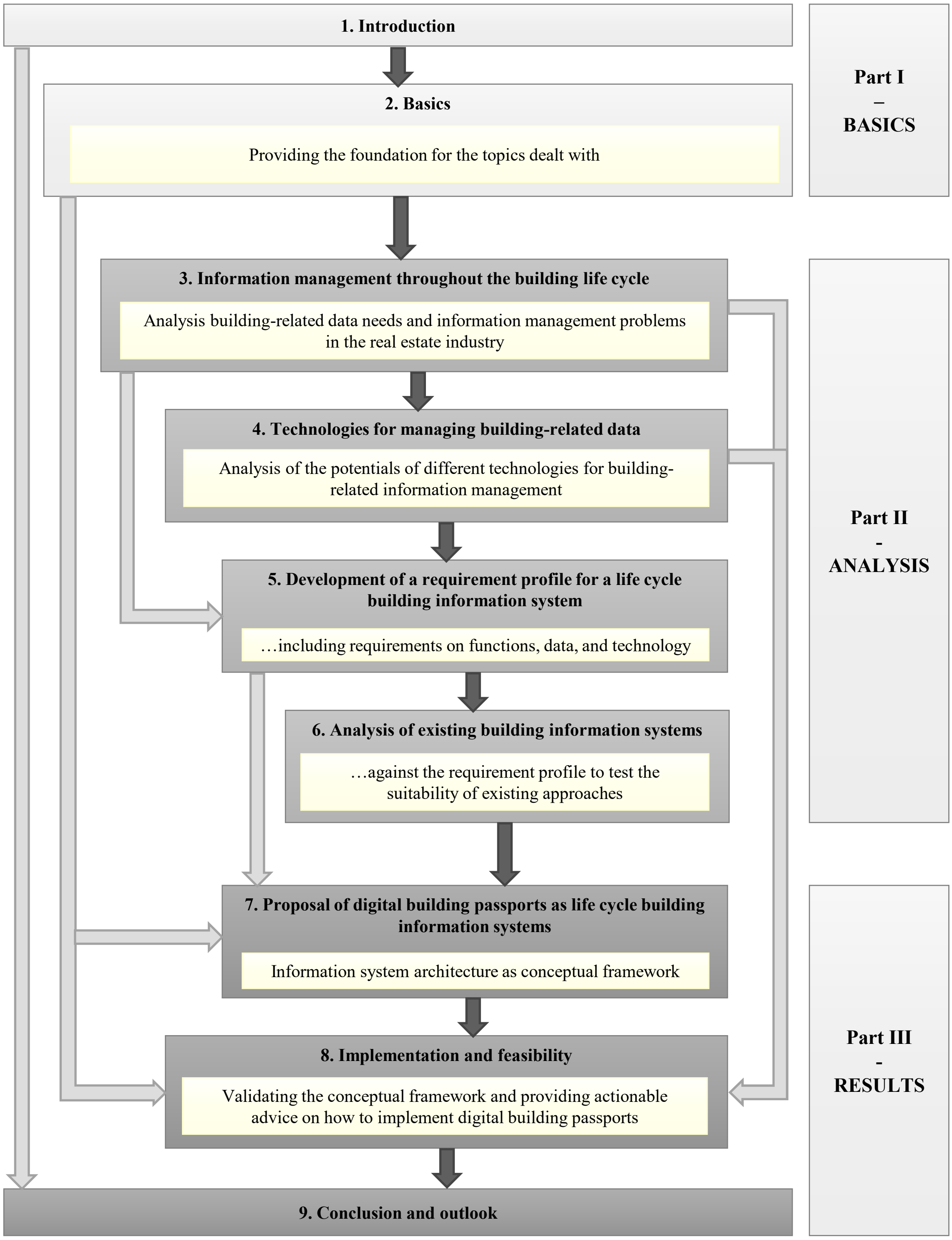



Figure 1.1: Outline of the thesis

# 2 Basics

*Chapter 2 provides the foundational knowledge essential for understanding the topics and explanations presented throughout this thesis. The interdisciplinary nature of the research is reflected in the following sections. First, key terms and concepts from the real estate industry are introduced to clarify the tasks and objects of focus within the research discipline (section 2.1). In section 2.2, basics of information management are introduced which includes selected insights from business informatics. In addition, basics of information modeling are described (section 2.3), before a brief overview of the current state of knowledge on information systems for real estate management is given (section 2.4).*

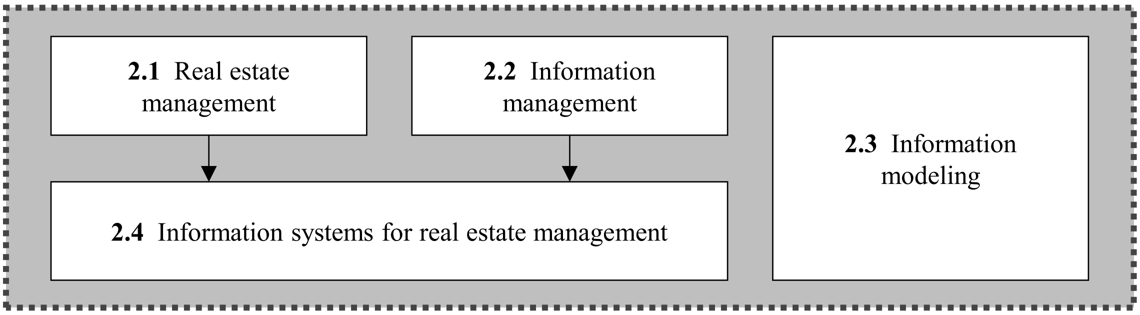



Figure 2.1: Structure of chapter 2

## 2.1 Real estate management

The fundamentals of real estate management form the background for the examination of more specific issues in this thesis. Recognized definitions of the term real estate and the real estate industry are briefly presented (sections 2.1.1 and 2.1.2). The consideration of the entire life cycle of a building, divided into characteristic phases, forms an important basis for many current questions in theory and practice. Therefore, the relevant basics are explained in section 2.1.3. Furthermore, the tasks, which come into play in the various processes of managing buildings throughout their life cycle (section 2.1.4), are of particular importance for the rest of this thesis.

### 2.1.1 Real estate and buildings

#### 2.1.1.1 Definition and dimensions of real estate

Real estate is central to real estate activities. However, the concept of real estate can be understood in varying ways, depending on the perspective and interests involved. In real estate research, a comprehensive understanding of the term has emerged, accounting for the diverse perspectives and objectives associated with real estate. This includes not only a physical delineation but also economic and legal dimensions (Bone-Winkel, Focke, & Schulte, 2016, p. 5). Additionally, real estate can be defined as an artificially delimited space extended by a temporal dimension (Rottke, 2017a, p. 142). This temporal dimension serves as the foundation for life cycle considerations of buildings.

Natural and legal persons use and operate real estate for various purposes, driven by different objectives for creating benefits. From an economic perspective, real estate provides diverse opportunities for use and is not limited to a single specific benefit (Bone-Winkel, Focke, & Schulte, 2016, p. 9). It plays a vital role in housing, addressing a fundamental human need, and, at least on the surface, serves as a consumer good. Additionally, real estate functions as an investment vehicle and capital good, fulfilling economic roles such as serving as a means of production, supporting trade, and enabling service activities (Bone-Winkel, Focke, & Schulte, 2016, p. 10). Bone-Winkel, Focke, and Schulte (2016, p. 15) synthesize these perspectives on differentiation and the functions of real estate into an attempt to provide a holistic definition of the term "real estate":

> *„Real estate is an asset consisting of undeveloped land or developed land with associated buildings and outdoor facilities. It is used by people within the framework of physical-technical, legal, economic and temporal limits for production, trade, service and consumption purposes.“[1] (Bone-Winkel, Focke, & Schulte, 2016, p. 15) (translated)*

The physical dimension is perhaps the most intuitive definition of real estate. It refers to the tangible existence and material attributes of a property, commonly referred to as construction work or building. A building is defined as a usually enclosed structure primarily serving as a protective device for its users and contents (DIN EN 15978:2024-05, p. 11). This protection is achieved through an envelope that artificially separates the building from its surroundings, a feature also highlighted in definitions of the physical dimension of real estate (Bone-Winkel, Focke, & Schulte, 2016, p. 5).

A building is composed of various elements, each serving distinct functions. In theory, 'elements' typically refer to physical building components or products that constitute building objects (DIN EN 15643:2021-12, p. 12; DIN EN ISO 16739-1:2021-11, pp. 11–13). In practice, however, there are ambiguous interpretations of these terms. A common distinction is made between structural building components and building services.

Real estate encompasses not only building elements but also the underlying land, as highlighted in the definition of real estate. This broader understanding reflects the combined significance of both the physical structures and the land they occupy. From this point forward, the term "building" will be predominantly used for simplicity, while "real estate" will be employed where necessary to emphasize the inclusion of the underlying land.

[1] Definition in original language: „Immobilien sind Wirtschaftsgüter, die aus unbebauten Grundstücken oder bebauten Grundstücken mit dazugehörigen Gebäuden und Außenanlagen bestehen. Sie werden von Menschen im Rahmen physisch-technischer, rechtlicher, wirtschaftlicher und zeitlicher Grenzen für Produktions-, Handels-, Dienstleistungs- und Konsumzwecke genutzt.“ (Bone-Winkel, Focke, & Schulte, 2016, p. 15)

#### 2.1.1.2 Specificities of real estate

One aspect explored extensively in the literature is the unique characteristics of real estate. The broad definition of the term and its implications already highlight the multifaceted nature of real estate. Historically, these distinct characteristics were a key reason for the establishment of real estate economics and management as a separate research field. In the context of this thesis, attributes such as location dependency, heterogeneity, and high capital intensity implicitly serve as important constraints and points of reference. Comprehensive lists and detailed explanations of these characteristics are available in the literature, such as in Rottke (2017c, pp. 41–47) or in Bone-Winkel, Focke, and Schulte (2016, pp. 15–20).

#### 2.1.1.3 Building use types

Real estate is inherently unique. However, dividing buildings into different types has become common in theory and practice to better capture typical features. One approach is to classify buildings based on their user groups. This method, however, is considered problematic due to the overlap in user groups and the ambiguous assignment of buildings to specific categories (Arens, 2016, p. 84). Another approach involves classifying buildings by characteristics such as size, location attractiveness, amenities, or energy quality. These classifications are typically used to assess specific building attributes (Pfnür, 2011, p. 8; Rottke, 2017a, pp. 146–147).

The most common method for basic grouping, however, is to classify buildings by their function (Arens, 2016, pp. 84–85). This involves distinguishing between the original function of a building and the broader purpose it serves. For instance, categorizing buildings as "commercial real estate" is criticized for not reflecting their original function, as various types of real estate can serve commercial purposes (Rottke, 2017a, pp. 147–148). Figure 2.2 illustrates a more recent approach for a potential classification that tries to overcome former ambiguities for commercial real estate.

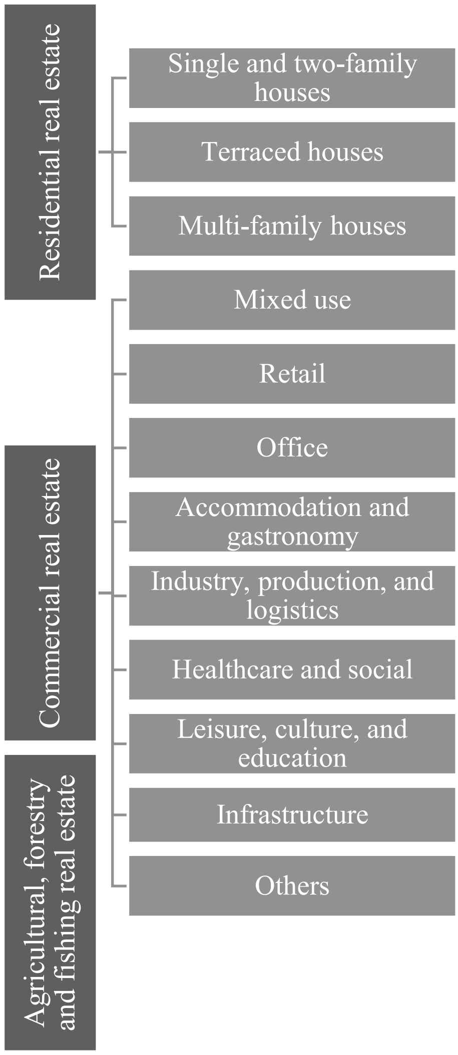



Figure 2.2: Classification of building use types based on their main function based on Zentraler Immobilien Ausschuss (2023, pp. 80–83)

## 2.1.2 Actors of the real estate industry

### 2.1.2.1 Actor perspectives on real estate

The real estate industry, as defined in more detail in section A.1.1, comprises a variety of actors, each playing a significant role in shaping decision-making processes related to real estate. These actors highlight the human factor in the industry, as their actions and decisions are often driven by distinct interests. An actor is defined as a "person, an organization, or a person that acts on behalf of an organization" (DIN EN ISO 16739-1:2021-11, p. 10). Actors can be characterized based on their perspective on real estate. Three primary perspectives dominate in theory and practice (Kämpf-Dern & Pfnür, 2009, pp. 16–18; Pfnür, 2011, p. 24):

- Return-oriented perspective (owner perspective): Reflects the interests of property owners and related service providers, emphasizing financial objectives and property-related value orientation. The goal is to maximize the capital invested in a property.
- Performance perspective (technological perspective): Concentrates on actors involved in the production and service processes during a building's life cycle, viewing the building as the subject or result of planning, construction, and operation.
- Use-oriented perspective: Focuses on actors who use real estate as a means of operation or a production factor.

In practice, different actors do not necessarily take in only one perspective. A listed housing company for example primarily follows motives from the return-oriented perspective, but takes in a performance perspective when developing and constructing new buildings and a use-oriented perspective for its office buildings.

#### 2.1.2.2 Actor roles

Fundamentally, different actor groups are associated with individual interests, although in practice, individual actors may assume particular roles that align with their main perspective on real estate. Roles are often closely related with the tasks actors perform in the building life cycle. However, roles are not exclusive to different types of actors who can take in multiple roles throughout the life cycle depending on the context. The relation between actors (i.e. their legal status), roles, and perspectives is illustrated in Figure 2.3.

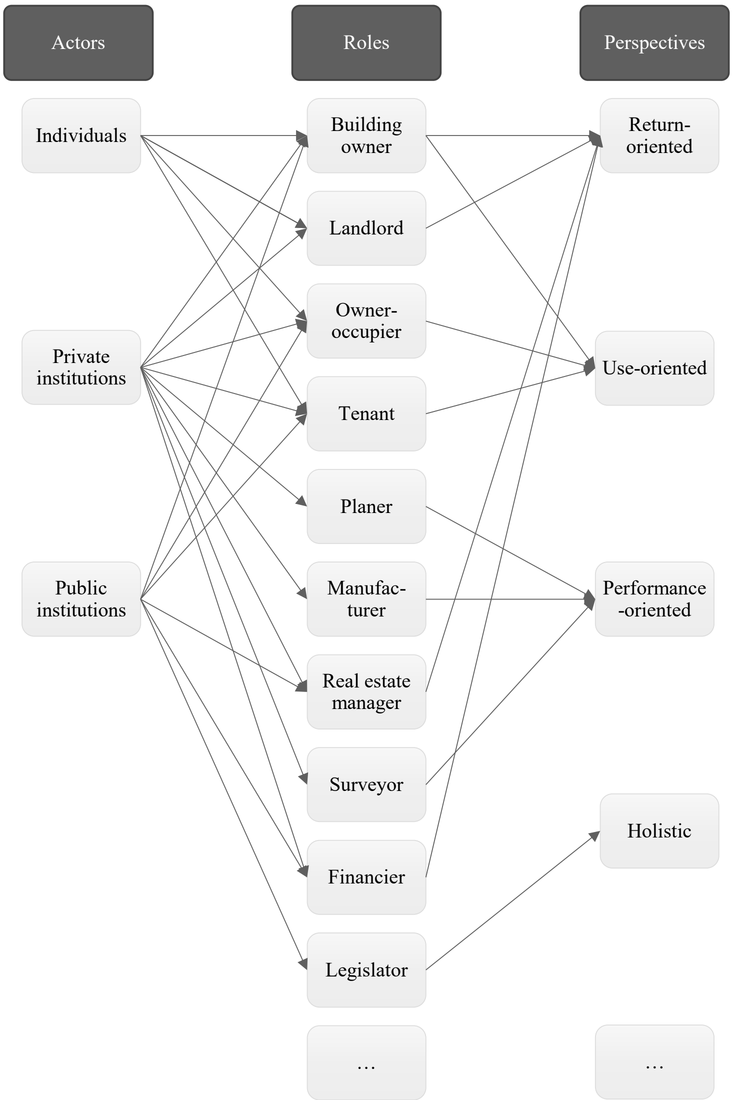



Figure 2.3: Relation between actors, their roles in the real estate industry, and main perspectives based on Enseling et al. (2023, p. 116)

Figure 2.3 only shows a snippet of actor roles in the real estate industry. Roles dynamically evolve according to the needs of different tasks.

#### 2.1.2.3 Classification of actors

To better comprehend the individual motives, needs, and actions of actors, it is helpful to classify actors into groups. Various approaches in the literature offer criteria for identifying and categorizing actor groups in the real estate industry. Key criteria include:

- Differentiating actors by their role in the real estate market, such as suppliers, buyers, and potentially "implementers" or service providers (Hellerforth, 2012, p. 4)
- Allocating actors to specific life cycle stages of a building (Brauer, 2019a, p. 27)
- Categorizing actors based on their activities or functions (ZIA, 2015, p. 11)
- Distinguishing actors by their perspective on real estate (Pfnür, 2011, p. 28)

- Differentiating actors by legal aspects, such as legal entities (institutions) and natural persons (private individuals) (Deplace et al., 2016, p. 27)
- Dividing actors into building owners and stakeholders (Deplace et al., 2016, p. 36)

A straightforward yet effective method is to functionally categorize actors based on their primary perspective on real estate combined with their main role (Table 2.1). While this approach may not provide the highest level of specificity, it enables logical grouping of tasks across the building life cycle and is more concise than more detailed approaches for defining functional clusters, such as those described in ZIA (2015, p. 11).

Table 2.1: Classification of actors in the real estate industry based on their main perspective and role

| Performance perspective | Return-oriented perspective | Use-oriented perspective |
|---|---|---|
| Building product manufacturers | Building owners (landlords and owner-occupiers) | Organizations as tenants |
| Project developers | Portfolio managers | Private individuals as tenants |
| Project managers | Asset managers | |
| Planers | Property managers | |
| Construction companies | Facility managers | |
| Craftsmen | Building managers | |
| Energy consultants | Financiers, banks | |
| Building experts and surveyors | Insurances | |
| Auditors and certifiers | | |
| Utility companies | | |
| Waste management companies | | |
| Facility services | | |

In some cases, the perspectives and roles of actors are merged to create a unique perspective based on several motives. This is the case for the public sector, which does not only act as builder, owner, and user of real estate, but above that as regulative authority.

Actors in the real estate industry interact on various occasions throughout the building life cycle, forming diverse constellations depending on the situation (Enseling et al., 2023, p. 99). Given the wide range of actors and circumstances, numerous actor constellations can emerge. A single actor may assume different roles across these constellations. As the number of actors involved grows, these constellations can evolve into networks.

### 2.1.3 The life cycle of buildings

Life cycle considerations are crucial for buildings due to their longevity and complexity. In standardization, the life cycle of a building is defined as all successive and interconnected stages of its existence (DIN EN 15643:2021-12, p. 17). More broadly, the life cycle of products encompasses the period from the initial idea to final disposal (DIN ISO 15226:2017-03, p. 7). These definitions involve dividing the life cycle into characteristic stages based on specified criteria, with logical connections and transitions. They also presuppose knowledge of the expected or actual service life.

In real estate-related contexts, the "object under consideration" typically refers to the building itself, although life cycles can also be examined for individual building elements. For buildings, proposals exist to divide the life cycle into four primary stages: manufacturing, construction, use, and end-of-life (DIN EN 15804:2020-03, pp. 20–22; DIN EN 15978:2024-05, p. 30) These stages can be further subdivided into more specific phases or task areas (Figure 2.4).

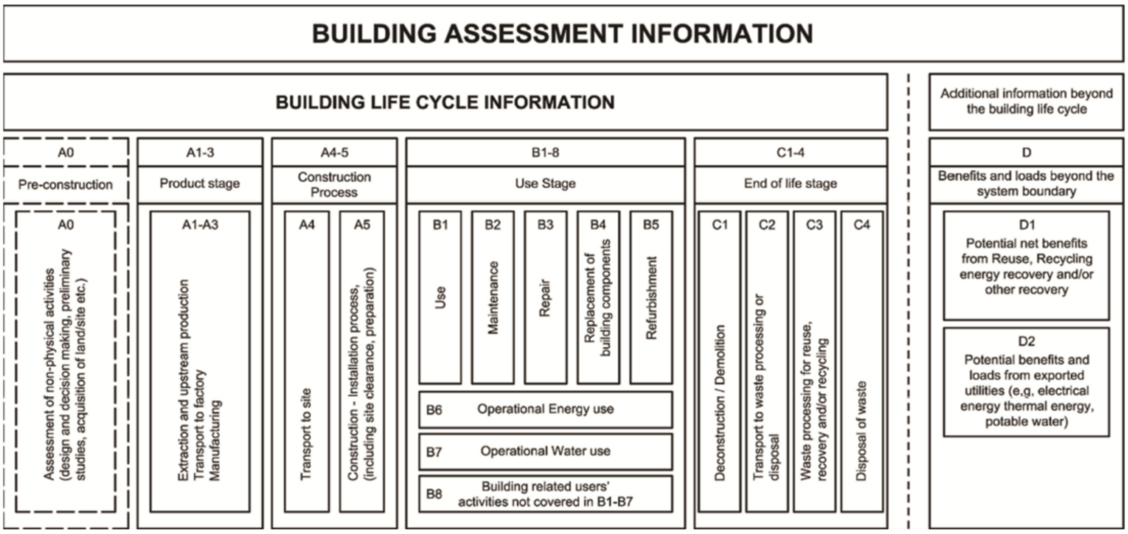



Figure 2.4: Builing life cycle definition in the context of sustainability assessments (DIN EN 15978:2024-05, p. 28)

The approach presented for defining the life cycle in standardization focuses on the physical dimension of a building by considering its current condition. This results in typical life cycle stages that reflect, through their designations, the predominant processes of the construction and real estate industry at each stage. For example, the construction stage refers both to the building's current state ("under construction") and to the process of construction itself.

Another critical aspect of the building life cycle, particularly relevant for assessments, is the point in time at which a life cycle stage is perceived. For instance, during the construction stage, the use stage is projected, during the use stage, it is the present focus, and during modernization or deconstruction, it is retrospectively analyzed.

In addition to dividing the life cycle into stages, the definition addresses the service life of a building. Different types of service life are distinguished, including:

- Actual service life: The realized lifetime of a building, from creation to deconstruction or deep renovation.
- Useful life: The period during which a building is actively used.

- Technical service life: The period until the building can no longer fulfill its function. This depends on the initial utilization potential, which determines the "wear and tear stock" and the actual wear and tear during the utilization phase.
- Economic service life: The period until an alternative use of the building becomes more profitable. This is influenced by the condition and quality of the building itself and exogenous factors such as market and societal developments (Kurzrock, 2017, p. 424).

Practitioners in the real estate industry are generally less familiar with standardized definitions of the building life cycle. Instead, they view it through the lens of the tasks they perform. Rather than focusing on the building's state at different stages, they consider time-phased task areas. The building life cycle typically begins with project development, followed by planning and construction, including project management. During the use stage, the emphasis shifts to operations rather than actual usage. Finally, the end-of-life stage is characterized by a process of building exploitation, differing from the end-of-use defined in the physical life cycle (Table 2.2).

Table 2.2: Comparison of life cycle definitions from a building and task-oriented perspective based on (Alda & Hirschner, 2016; Ausschuss der Verbände und Kammern der Ingenieure und Architekten für die Honorarordnung [AHO], 2020; DIN EN 15978:2024-05)

| Life cycle standardization (building perspective) | Task-oriented life cycle stages (performance perspective) |
|---|---|
| Production<br>• Raw material supply (A1)<br>• Transport (A2)<br>• Manufacturing (A3) | Project development<br>• Initiation<br>• Conception |
| Construction<br>• Transport (A4)<br>• Construction/installation (A5) | Construction project management<br>• Project preparation<br>• Planning<br>• Execution preparation<br>• Execution<br>• Project completion |
| Use<br>• Use (B1)<br>• Maintenance (B2)<br>• Repair (B3)<br>• Replacement (B4)<br>• Refurbishment (B5)<br>• Operational energy use (B6)<br>• Operational water use (B7)<br>• Additional user activities (B8) | Operation<br>• Facility management<br>• Technical building management<br>• Infrastructural building management<br>• Commercial building management<br>• Space management |
| End-of-life<br>• Deconstruction/demolition (C1)<br>• Transport (C2)<br>• Waste processing (C3)<br>• Disposal (C4) | Exploitation<br>• Disinvestment<br>• Deconstruction/demolition<br>• New project development |

There are proposals to integrate both life cycle perspectives into a unified approach, resulting in a hybrid building life cycle that combines key task stages with the fundamental stages of a building's state (Mehlis, 2005, p. 21). A hybrid approach with a stronger focus on engineering tasks is also reflected in standardization (DIN EN 16310:2013-05, p. 13).

A similar approach was taken to merge the life cycle perspectives laid out in Table 2.2.

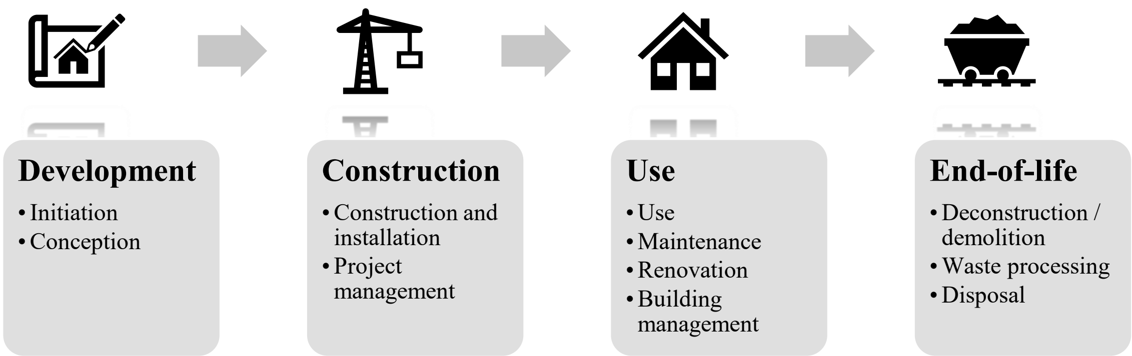



Figure 2.5: Integrated building life cycle

The integrated life cycle, as illustrated in Figure 2.5, will serve as a basis for further life cycle considerations throughout this thesis.

### 2.1.4 Tasks in the building life cycle

#### 2.1.4.1 Classification of tasks

Kämpf-Dern and Pfnür (2009, p. 14) propose a definition for real estate management based on three dimensions: the main actor perspective (section 2.1.2.1), the building life cycle stage, and the management level. The life cycle dimension comprises three phases: design/construction, use/operation, and exploitation. The management dimension refers to three institutional levels: corporate, portfolio, and building (Figure 2.6). Together, these dimensions form a three-dimensional framework that facilitates the classification of real estate management tasks (Kämpf-Dern & Pfnür, 2009, p. 14).

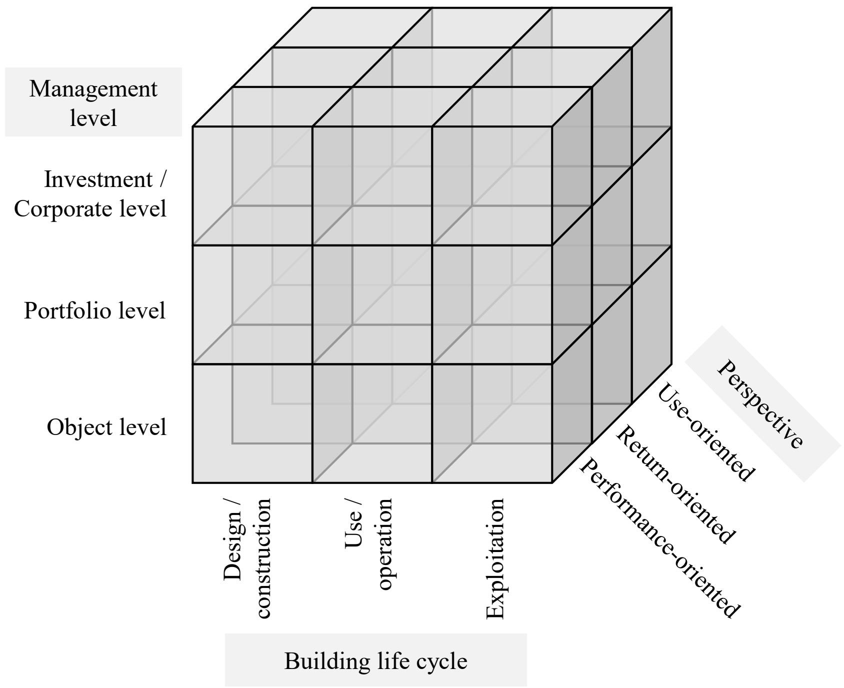



Figure 2.6: Three-dimensional framework for real estate management (Kämpf-Dern & Pfnür, 2009, p. 14)

For a more thorough specification of building-related tasks, the main perspectives from the framework are applied in the following sections.

#### 2.1.4.2 Tasks from the return-oriented perspective

Tasks from the return-oriented perspective can best be described using different levels of real estate management. These levels differ in their primary focus (normative, strategic, or operational) and scope.

At the investment management level, also referred to as corporate level, the focus is normative and strategic, encompassing tasks related to business administration, business segments, and building stock (Figure 2.7). Responsibilities include developing real estate management strategies that align with corporate goals and guiding investment decisions. This level often integrates traditional business management functions, such as accounting, corporate governance, and sustainability reporting, with real estate management objectives (Kämpf-Dern, 2009, pp. 6–7).

The portfolio management level focuses strategically on the building stock as a whole. It involves the systematic development and management of the portfolio in accordance with corporate strategies and predefined specifications (Kämpf-Dern, 2009, p. 8).

The building level, comprising asset management, property management, and facility management, operates at both strategic and operational levels.

- Asset management focuses on individual buildings, identifying value enhancement opportunities and formulating strategies aligned with investor goals.
- Property management implements these strategies with a focus on tenant relations, cost management, and achieving return-oriented outcomes.

- Facility management emphasizes the operational aspects of maintaining and optimizing building functionality and efficiency (Kämpf-Dern, 2009, pp. 9–15).

The tasks on the building level are closely connected with each other, especially in practice (Pelzeter & Trübestein, 2016, p. 289). A holistic real estate management approach requires close cooperation across all levels: upper levels define requirements for lower ones, while lower levels report relevant building-related data and information upward. This interdependence highlights the critical role of information management. Kämpf-Dern (2009, pp. 6–13) outlines these levels and their tasks, emphasizing the importance of collaboration to ensure effective management. Figure 2.7 provides a visual representation of the hierarchy and interactions across these levels.

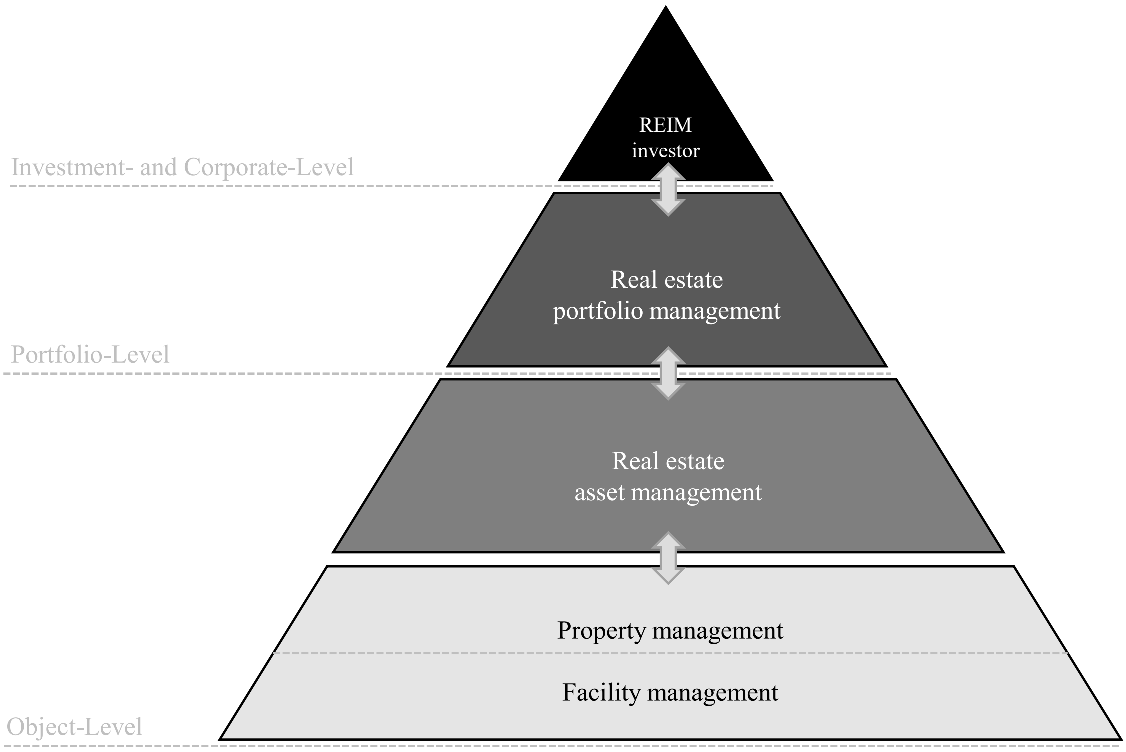



Figure 2.7: Levels of real estate management based on Teichmann (2009, p. 58)

In addition to tasks that can be clearly assigned to specific management disciplines within real estate management, certain task areas have emerged that are relevant across multiple stages of the building life cycle (Table 2.3).

Table 2.3: Cross-functional tasks in the building life cycle based on (Feldmann et al., 2016; Leopoldsberger et al., 2016; Rock & Hennig, 2016; Rottke, 2017b; Schulte, Sotelo, et al., 2016)

| Task area | Specification |
|---|---|
| Building analysis | …basically includes all types of economic, environmental, social, technical, legal or other analyses mostly with the goal to determine the advantageousness of an action alternative with regard to the actor-specific goals and framework conditions. |
| Property valuation | …includes several approaches and methods to determine the economic value of a property which is of interest at numerous occasions in the building life cycle, such as project development calculations, transactions, financing, insuring, portfolio analyses, accounting, tax purposes, or legal cases. |
| Financing | …task of finding suitable solutions for the financing of real estate investments, major construction works or building-related services. |
| Investments | …includes all tasks that are related of determining real estate as an investment vehicle. |
| Risk management | …an integrative task of many other tasks, such as portfolio management, while also interpretable as an overarching task area to deal with risks and uncertainties. Typically connected to cost-benefit analyses, property valuations, financing and credit checks, construction realizations, or insuring. |
| Marketing | …all systematic and targeted activities designed to promote and facilitate the sale, rental, or provision of real estate and related services. |

These cross-functional tasks play a crucial role throughout the building life cycle, supporting decision-making and enabling actors to address key economic, technical, and strategic challenges.

#### 2.1.4.3 Tasks from the performance perspective

Actors within the performance perspective engage in planning, construction, and operation across the building life cycle. The earliest task area is real estate project development, which focuses on processes rather than the physical building itself. Project development can be defined narrowly, limited to initiation and conception stages, or broadly, covering the entire building life cycle (Alda & Hirschner, 2016, p. 23). Given its process-oriented nature, project development tasks may commence at different points in the life cycle, depending on whether it involves new construction or deconstruction (Alda & Hirschner, 2016, p. 27).

The construction stage follows production and involves project management, which ensures proper project execution. The boundaries between project development and project management are fluid. Generally, all necessary preparations must occur during project initiation and conception, with some definitions including a project concretization stage before realization (Bone-Winkel, Isenhöfer, et al., 2016, p. 206). Project management formally includes the tasks, organization, techniques, and resources required for initiation, planning, execution, and completion (DIN 69901-5:2009-01, p. 14). In Germany, the construction project management framework is detailed in AHO booklet 9 (AHO, 2020), outlining specific performance profiles across preparation, planning, execution, and completion stages.

Design is a key component of project management but is also an independent discipline with significant influence on economic, environmental, and social performance. It typically involves designing a building's structural, functional, and service-related elements, requiring close collaboration among experts to meet investor, user, and regulatory expectations (Diederichs, 2005, p. 270).

The role of facility and building management in real estate perspectives is debated, but facility services clearly fall under performance-oriented tasks. Standardization differentiates building management as the operational aspect of facility management during the use stage (DIN EN ISO 41011:2019-04, p. 6). Facility management is a cross-life cycle discipline ensuring user-oriented real estate management (Preuß & Schöne, 2016, p. 628), whereas building management focuses on technical, infrastructural, and commercial aspects during operation (DIN 32736:2000-08, p. 2; Hirschner et al., 2013, p. 5).

A critical task within the performance perspective is maintenance management, addressing structural and component wear during the use stage. Maintenance is defined as the sum of technical, administrative, and managerial measures to preserve or restore functionality (DIN 31051:2019-06, p. 4). (DIN 31051:2019-06, p. 4). It includes routine maintenance, inspection, repair, and improvement (Figure A.1). Beyond material wear, buildings can lose value due to outdated technology or shifting user demands. Modernization mitigates this by incorporating technological advances and evolving requirements (DIN EN 13306:2018-02, p. 37). Terms such as renovation (restoration and renewal), refurbishment (comprehensive improvement), and retrofit (system upgrades, often for energy efficiency) describe related processes, though their definitions lack standardization.

The end-of-life stage includes demolition activities. However, circular economy principles are driving greater emphasis on controlled deconstruction to enable material reuse. Deconstruction or demolition may result from reaching the building's technical or economic service life. Alternative pathways include vacancy, conversion, or refurbishment, leading to repeated use stages (Gondring, 2013, pp. 37–38). Despite these possibilities, technical and economic constraints generally limit the number of viable use cycles.

#### 2.1.4.4 Tasks from the use-oriented perspective

Pfnür (2011, p. 26) defines Corporate Real Estate Management (CREM) as the core organizational concept that constitutes the use-oriented perspective on buildings. CREM in the narrow sense deals with the management of buildings in their role as production factor. In the broader sense, CREM also takes in the return-oriented and the performance perspective on buildings (Pfnür, 2011, p. 26). This makes sense, since especially when building users are owner-occupiers, they have an original interest in the economic viability of a building. Moreover, they might take on tasks from the return-oriented and the performance perspective that are otherwise performed by experts.

The main goal of CREM is to provide buildings to business units according to their specific needs. For this, strategic and operative measures are needed in a performance-oriented approach which include analysis, planning, execution, controlling and assessment activities for buildings and related objects of consideration (Pfnür, 2011, p. 166; Schäfers, Gier, & Dietzel, 2016, p. 796).

These activities can occur at different stages in time throughout the whole life cycle of buildings and can be regarded as an iterative process as well: Institutions manage buildings according to their needs. Based on that, they need to plan the necessary building stock and identify options to provide buildings that meet the requirements. Existing building can be kept or sold, while new buildings might be acquired and eventually rebuilt or modified. As an alternative, buildings might be rented (Pfnür, 2011, p. 172).

From a strategic point of view, the real estate strategy must be aligned with the corporate strategy (Glatte, 2021, p. 13). Corporate goals set the frame for real estate specific goals. In this sense, Schäfers, Gier, and Dietzel (2016, p. 804) distinguish between a first dimension of real estate specific goals consisting of input, structure, efficiency, and output goals and a second dimension of return-oriented, performance, and social goals that stay in relation to each other. After formulating specific goals, companies should derive strategies for the provision, management, and exploitation of real estate (Figure 2.8). This reinforces the similarities of tasks with the return-oriented and the performance perspective on real estate.

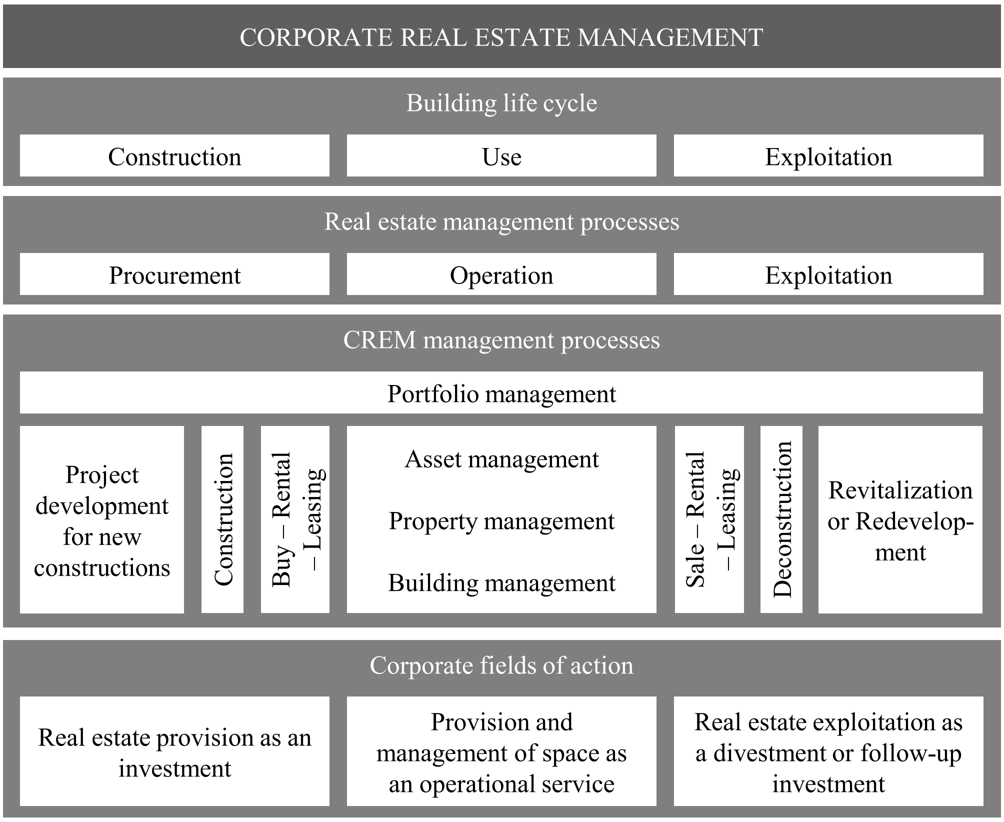



Figure 2.8: Overview on corporate real estate management (Glatte, 2014, p. 27)

For other types of building users, specific forms of real estate management have evolved that consider the specific motives and needs of the user. Therefore, differences to CREM exists. Examples include:

- Ecclesiastical real estate management: In countries like Germany, the church still owns a severe percentage of the building stock. Due to specific organization and the large amount of special property, a specific approach for the provision, management, and exploitation of buildings is needed (Cajias & Käsbauer, 2016, p. 872).
- Private real estate management specifies the motives, needs, and tasks of private real estate investments (Tilmes et al., 2016, p. 892).

In the core literature on real estate management, the perspective of private individuals does not receive a lot of attention. One reason can be that private individuals usually do not follow a systematic approach to manage buildings and that in some countries, such as Germany, a large proportion of the population does not possess real estate. However, the group of private home-owners is still very large with 16 million people (Haus & Grund, 2023). In terms of managing the national building stock, ensuring affordable and available living space for the society, pursuing sustainability goals etc. this group takes in a very important role and will thus be considered throughout this thesis.

#### 2.1.4.5 Public sector tasks

The public sector plays a unique role in the real estate industry, assuming multiple functions and integrating all major perspectives on real estate. Public institutions act as landlords, builders, building users, and operators, often being expected to serve as a role model in sustainable and responsible real estate management (Hennig et al., 2019, p. 8). For these roles, the term Public Real Estate Management (PREM) is used in the literature (Schäfers, Ecke, et al., 2016, p. 843). At the same time, the public sector, at federal, state, and municipal levels, acts as a legislator, establishing the regulatory framework that governs relationships between private and institutional actors. Additionally, municipal building authorities manage building permits and coordinate information flows with building owners and other stakeholders, while the public sector also serves as a jurisdictional authority in legal cases.

As a legislator, the public sector is involved in a broad range of real estate-related activities, including:

- Urban and spatial planning
- Construction and permitting processes
- Funding programes and social policy
- Environmental and climate protection
- Disaster management and safety
- Taxes and finances
- Public construction projects
- Transport and mobility
- Law enforcement and regulatory policy (Enseling et al., 2023, pp. 95–96; Krause et al., 2022, pp. 27–28; Schäfers, Ecke, et al., 2016, pp. 839–848)

These responsibilities illustrate the public sector’s dual role as both a market participant and a regulatory authority, influencing real estate markets through both direct ownership and policy-making.

## 2.2 Information management

Efficient handling of building-related data requires actors in the real estate industry to engage with technological advancements and align their practices with the evolving digital landscape. At the core of these efforts lies information management, which serves as a bridge between technological capabilities and real-world applications. To fully explore the role of technology in real estate, it is necessary to first establish a clear understanding of the key concepts and principles that define information management.

Within this section, the fundamentals of information management are systematically prepared, including the definition of key terms (section 2.2.1), the relevance of data sharing (section 2.2.2), and the introduction to information systems (section 2.2.3). In addition, aspects on the underlying technology will be explained (section 2.2.4), before wrapping it up with a holistic perspective on the functionality of information management (section 2.2.5).

This section leverages classifications and methodologies from information science and business informatics, domains which has so far been barely integrated with real estate management.

### 2.2.1 Data, information and knowledge

#### 2.2.1.1 Definition of relevant terms

In everyday language, distinctions between terms like data, information, news, and knowledge are often blurred. While there is still no universally accepted definition of "information" (Krcmar, 2015, p. 11), most proposed definitions stem from information science and, increasingly, economics. The differing methodologies of these disciplines are a key reason for the variation in definitions. To address these discrepancies, interdisciplinary approaches, such as those in business informatics, are gaining traction and aiming to bridge the gap (Engelmann & Großmann, 2021, p. 4).

Figure 2.9 illustrates a widely used definition of the terms symbol, data, information, knowledge, and wisdom through the concept of the so-called knowledge pyramid. According to this model, symbols represent the basic elements. Data are created by applying syntactic rules to symbols. By adding context, data can be transformed into information. When information is interpreted as an object of experience in relation to other information, it becomes knowledge. Wisdom, at the top end of the hierarchy, builds on knowledge and incorporates the competency of judgement (Ackoff, 1989, pp. 3–9; Engelmann & Großmann, 2021, pp. 5–6). Critics of the knowledge pyramid argue that the concept of information cannot be universally valid, as it is neither universally known nor consistently stored. Information is stored differently on physical media and in human consciousness, leading to varying interpretations and limitations (Frické, 2009, p. 140).

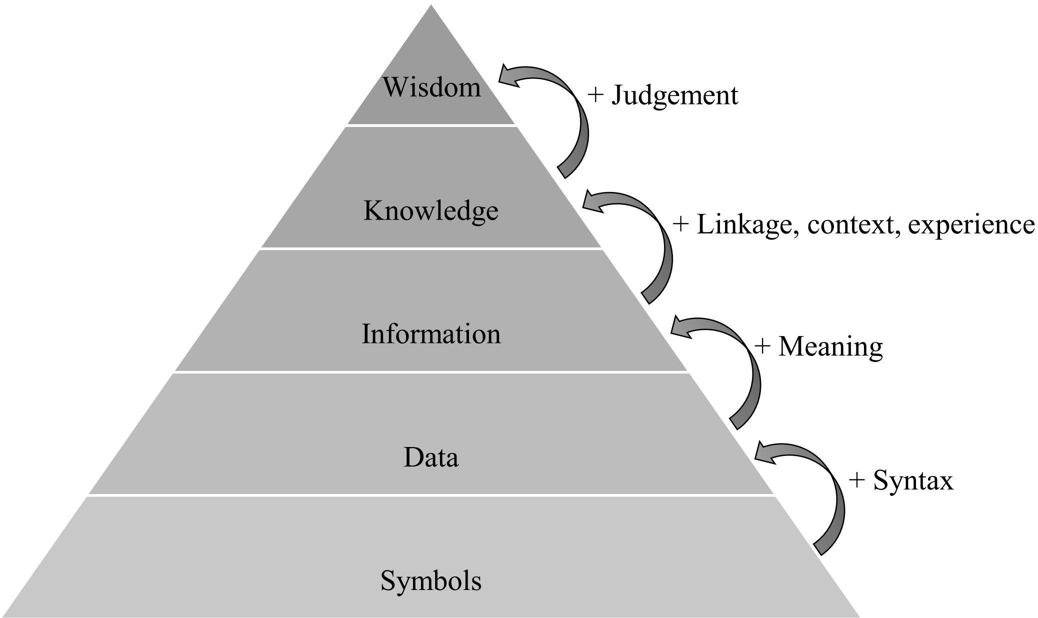



Figure 2.9: Knowledge pyramid based on Ackoff (1989, pp. 3–9) and Engelmann and Großmann (2021, p. 6)

Alpar et al. (2019, p. 6) refine the classic definition of information, traditionally understood as purpose-oriented knowledge. They propose that information is not a static component of existing knowledge but rather a dynamic variable, representing additional knowledge. Information is represented on a storage medium through data (Alpar et al., 2019, p. 7). This perspective contrasts with the earlier explanation that information can only arise from data. For instance, Schütte (1998, p. 3) considers data as a specific subset of information, characterized by the need for a structured understanding of the world. The distinction between data and information is particularly evident in their collection (Schütte, 1998, p. 3). Whether data constitutes information depends on the knowledge of the recipient (Alpar et al., 2019, p. 7).

#### 2.2.1.2 Value of data and information

Information plays a critical role in decision-making and problem-solving by providing meaning to the informed party. The benefit of information depends on its ability to reduce the uncertainty faced by decision-makers, thereby supporting their decision-making processes. In information science, this value is quantitatively measured using the entropy function. The value of the function reflects two factors: the initial uncertainty and the potential of the information to reduce this uncertainty (Alpar et al., 2019, pp. 8–15).

Information is also viewed as a versatile good in the economic context, fulfilling multiple functions. From a production economics perspective, it acts as a factor of production, from a decision theory perspective, it serves as a tool for preparing decisions, and from a strategic perspective, it provides a competitive advantage. Furthermore, new institutional economics considers information within the framework of individuals' actions and decision-making processes, emphasizing how it influences behavior and outcomes (Engelmann & Großmann, 2021, p. 4). Picot and Reichwald (1990, pp. 247–249) further identify four core functions of information: decision support, management, control, and documentation. These functions highlight the multifaceted role of information in shaping organizational processes and achieving objectives.

Compared to tangible economic goods, information poses particular challenges in determining its economic value. These arise not only from its abstract nature but also from its unique behavior in production, distribution, and usage. A number of defining characteristics set information apart from material goods:

- Intangibility and non-depletability, meaning it is not consumed through use (Krcmar, 2015, p. 16)
- Low reproduction costs and near-instantaneous duplicability (Krcmar, 2015, p. 17)
- Combinability and independence from physical carriers, allowing for simultaneous existence in multiple formats and locations (Kaufmann & Meier, 2023, p. 1)
- No physical aging and value evolution through aggregation, selection, or omission (Kaufmann & Meier, 2023, p. 1)
- Low duplication costs and high transportability, while quality and valuation remain difficult (L. J. Heinrich et al., 2011, p. 155)
- Diffusion tendency and vulnerability to manipulation, even at high transmission speeds (Picot & Reichwald, 1990, pp. 250–251)

These attributes make information highly versatile but also present challenges in determining its economic value, as its utility is context-dependent and influenced by the trustworthiness of its source and the purposes for which it is used.

Determining the value of information involves balancing its utility for problem-solving and decision-making processes against the costs of obtaining it. However, practical challenges arise due to the difficulty of quantifying both information costs and benefits and the assumption of perfect information availability. Furthermore, the "information paradox" complicates valuation: assessing the value of information requires prior knowledge of it, but once acquired, the information is already accessed, rendering valuation inherently retrospective. In organizational contexts, trust in the information source often replaces explicit valuation. Additionally, time and financial constraints typically limit information search activities, with acquisition ceasing when decision-makers identify sufficiently viable options for achieving acceptable outcomes (Picot & Reichwald, 1990, pp. 259–260).

#### 2.2.1.3 Difference between information supply, demand and need

In everyday language, the terms "information demand" and "information need" are often used interchangeably. However, there is a significant distinction between the two. Information demand refers to the actions of actors requesting information in any communication or data-sharing context. It is inherently subjective. In contrast, information need is objective and represents the information that actors should possess for a specific task or occasion. While actors in the economy strive to understand their information needs, this task becomes increasingly complex in today's information society.

In the real estate industry, the gap between information demand and information need can be particularly pronounced due to the unique characteristics of real estate. Picot and Reichwald

(1990, p. 276) provide a detailed framework, distinguishing between objective information need, subjective information need, information demand, and information supply (Figure 2.10). The intersection of these elements defines the “information stand” of actors, highlighting the alignment, or misalignment, between the information they seek, require, and possess.

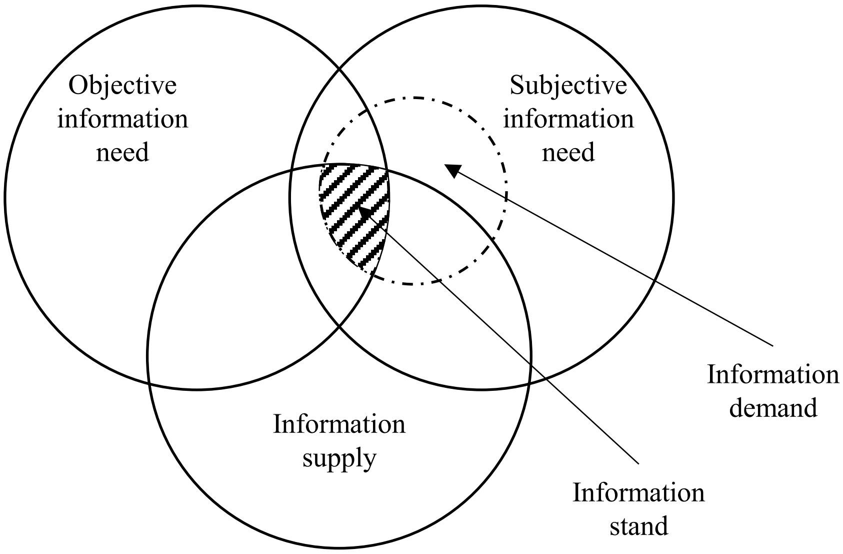



Figure 2.10: Information need and information supply based on Picot and Reichwald (1990, p. 276)

#### 2.2.1.4 Digital Data

Digital data are machine-readable and represented using predefined character sets. At the most basic level, they consist of binary digits (bits) with values of "0" or "1," reflecting the physical states of transistors in a computer. This binary system underpins all digital data processing. Higher-level encoding systems, such as ASCII (128 characters) and Unicode (over a million characters), define how text and symbols are represented, while specialized encodings exist for images, videos, and sound (Hansen et al., 2019, pp. 439–454).

Data are categorized by type, determining possible operations. Structured data, like records and arrays, organize multiple elements, while unstructured data lack such organization. Many data types reference others, forming relationships (Hansen et al., 2019, pp. 454–461).

A file is a collection of related data stored on a medium, with its format defining storage and encoding. Common file operations include opening, reading, editing, and deleting. Files may store text, images, videos, or programs. Digital documents are a specific type of file containing text (Hansen et al., 2019, pp. 461–462).

Figure 2.11 illustrates the connection of digital data representations in a hierarchy ranging from bits on the lowest level to databases on the top level.

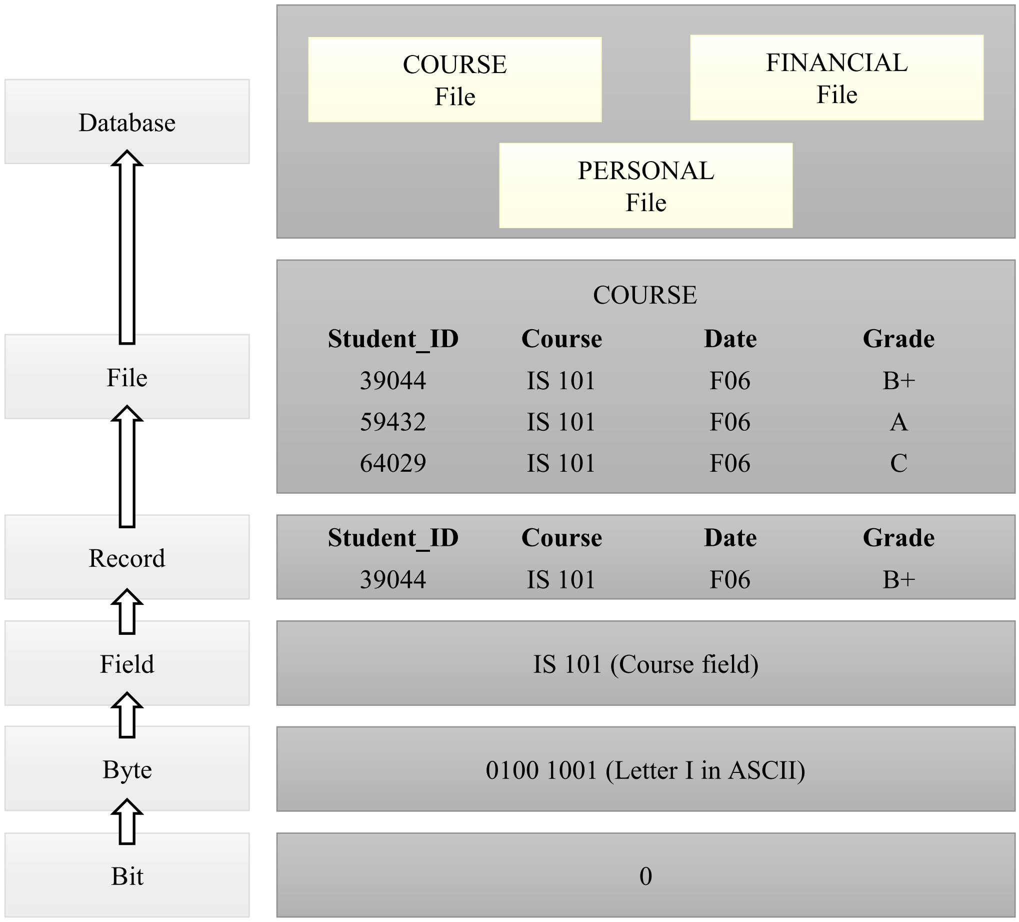



Figure 2.11: Data hierarchy with examples based on Laudon and Laudon (2014, p. 242)

## 2.2.2 Data exchange and sharing

### 2.2.2.1 Types of communication

When data are transmitted, it becomes a message, and the reciprocal exchange of messages constitutes communication (Alpar et al., 2019, p. 7). There are different forms of communication depending on the spatial and temporal distribution of communication participants. According to this, communication can be either collocated or remote as well as synchronous or asynchronous (Figure 2.12). Ongoing digitization has increased the possibilities of remote communication.

| | **Same time** synchronous | **Different time** asynchronous |
|---|---|---|
| **Same place** colocated | **Face-to-face interactions** (e.g., shared table, wall display, decision rooms, roomware, single display groupware) | **Continuous tasks** (e.g., team rooms, project management systems, shift work groupware, public display) |
| **Different place** remote | **Remote interactions** (e.g., video conferencing, instant messaging, chats, multi-user editor, screen sharing, virtual wall) | **Communication and coordination** (e.g., email, blog, bulletin board, wiki, group calendars, workflow, version control) |

Figure 2.12: Time-space matrix of communication forms (Borrmann, König, et al., 2018a, p. 261)

### 2.2.2.2 Communication between actors

Communication plays a crucial role in meeting the information needs of actors. According to Starzner et al. (2007, p. 17), actors assume various roles in communication, including data supplier, data processor or service provider, data consumer, and stakeholder. A simple communication model between a data supplier and a data consumer classifies them as sender and receiver (Figure 2.13). Communication can occur either directly or indirectly. In direct communication, participants exchange messages and data directly with one another. In contrast, indirect communication takes place through collaborative interaction with shared data resources, which act as centralized repositories. These repositories collect relevant communications and ensure transparency and comprehensibility in decision-making processes.

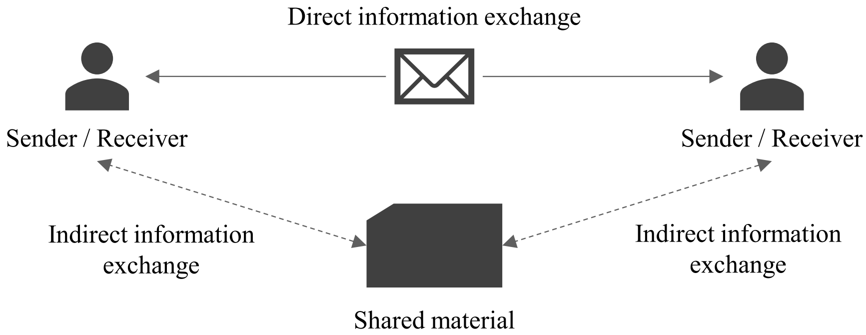



Figure 2.13: Comparison of data exchange and data sharing based on Borrmann, König, et al. (2018a, p. 261)

Communication processes vary significantly depending on factors such as their existence, type, and depth. Often, a communication process is initiated by the information demander, creating a pull effect. Conversely, when the information supplier initiates the communication, it generates a push effect. Signaling occurs when the sender deliberately communicates a particular state, ability, or quality, adding another dimension to the sender-receiver model (Picot et al., 2020, p. 27).

## 2.2.3 Information systems

### 2.2.3.1 Definition

Information systems link data and information and give them a context. Information systems, which represent the primary object of consideration in the field of business informatics, are conceptually composed of "information" and "system" (Alpar et al., 2019, p. 3). In this context, according to Alpar et al. (2019, p. 15), a system consists of "a set of interrelated elements that can be distinguished as a whole from their environment." Numerous definitions exist in the literature for information systems, also called information and communication systems in a broader sense. The majority of these overlap in the following characteristics for information systems. Information Systems...

- ... are socio-technical systems, i.e. they consist of machine and human elements.
- ...are artificially separated from their environment.
- ...consist of interrelated components that collect, structure, process, store, disseminate, transform, and make usable data, information, and knowledge.
- ...aim to support processes for decision-making, coordination, control, analysis, visualization, and automation of value-added processes in companies by providing their users with information (Alpar et al., 2019, p. 25; Gabriel, 2016; Laudon & Laudon, 2014, p. 612).

Furthermore, information systems are considered open systems, which means that they are connected to their environment and have corresponding interfaces. They are characterized by their complexity, which stems from the large number of elements. They also have a dynamic character: Elements can change their characteristics over time through interaction (Krcmar, 2015, p. 23).

### 2.2.3.2 Elements

As described, information systems are a mixture of human and machine elements. Machines, in this sense, are applications enabled by the use of associated hardware. Applications use data within processes to be executed, which in turn fulfill specific functions in the connection of different elements. The basic functioning of a socio-technical information system described in this way is illustrated in Figure 2.14.

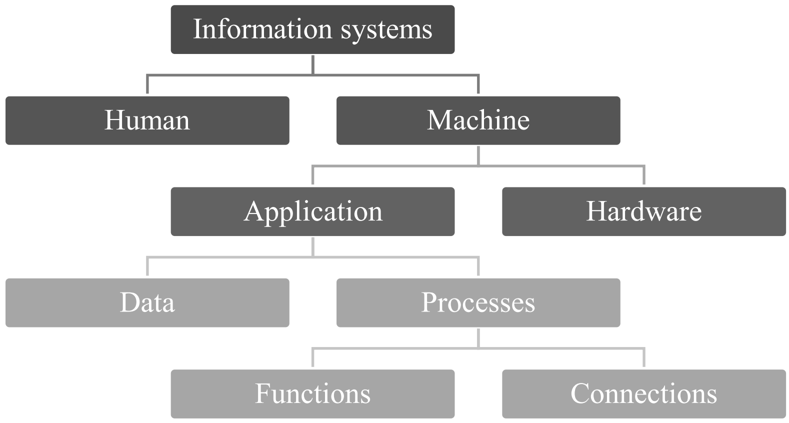



Figure 2.14: Information systems as human-machine systems based on Krcmar (2015, p. 22)

L. J. Heinrich et al. (2011, pp. 17–18) regard tasks as another crucial element in information systems, leading to an interpretation as human-task-technology systems. They refer to functional task areas in organizations.

#### 2.2.3.3 Types

In the information management literature, information systems are described in a business context and in a narrower sense as application systems. Application systems refer to all non-human elements of an information system (Alpar et al., 2019, p. 25). Against this background, some distinguishing features between different information or application systems can be formulated. For example, there are both company-based and inter-company systems, as well as sector-specific and cross-sector systems. In companies themselves, function-related information systems perform specific tasks, while company-wide systems are intended to reflect the information structure of an entire company. In terms of technical implementation, a distinction can be made between the use of standard and customized software (Alpar et al., 2019, p. 31; Krcmar, 2015, p. 23). Operational systems usually focus on a shorter period of time and, in contrast to strategic systems, are used for individual business functions (Gluchowski et al., 2008, p. 5).

Based on their main purpose in business activities, different categories of information systems can be identified. Table 2.4 lists typical categories from the literature. In practice, the distinction between the functions is not always clear, so that mixed forms are likely (Alpar et al., 2019, p. 29).:

Table 2.4: Types of information systems based on (Alpar et al., 2019, pp. 28–43; Gluchowski et al., 2008, pp. 6–8; Mertens, 2013, pp. 27–29)

| Type | Examples | Function |
|---|---|---|
| Transaction systems (systems of record) | Administration systems | Processing large volumes of data |
| | Disposition systems | Executing dispositive tasks |
| Management support systems (systems of insight) | Planning systems | Supporting strategic decisions |
| | Control systems | Monitoring objectives |
| | Reporting systems | Automated reporting |
| | Analysis systems | Supporting data analysis |
| Interactive systems (systems of engagement) | Platforms | Enabling interaction and collaboration |

#### 2.2.3.4 Architecture

Information system architectures (ISAs) serve to structure and organize the main elements of an information system. A recognized definition of the term ISA is: "Architecture is that set of design artifacts, or descriptive representations, that are relevant for describing an object such that it can be produced to requirements (quality) as well as maintained over the period of its useful life (change)" (Zachman, 1997, p. 5).

The approach to creating an ISA pursues the goal of creating a holistic overview at the interface between information-economic use and existing technological options for action. On the one hand, a structured view of an information system should be taken into account and on the other hand, a clear modeling should be pursued (Krcmar, 2015, p. 101). The architecture of an information system can also be understood as a construction plan, following the discipline of the same name for the planning of buildings (Baars & Kemper, 2021, p. 21).

Zachman (1997, p. 5), who is regarded as a co-founder of this scientific discipline, also developed a classification system for system architectures. According to this, the perspective (*Scope, Owner, Designer, Builder, Subcontractor, Product*) can be set in relation to a specific question (*What, How, Where, Who, When, Why*) in a two-dimensional view.

There are several proposals in the literature on how to design a holistic ISA including the one from Krcmar (1990, p. 399) and the one from Scheer (1991). In his model, August-Wilhelm Scheer defines four interdependent elements for structuring integrated information systems: organisation, control, data, and functions. Within each of these elements, there is a three-part hierarchy that illustrates the connections between conceptual modeling and technical implementation (Figure 2.15). This aspect is related to the concept of a three-schema architecture for information system and database design (ANSI-SPARC architecture) (Hansen et al., 2019, p. 467). The individual elements in information systems can form sub-architectures and comprise a data structure for example (Zachman, 1997, p. 4). According to Scheer (1991, p. 20), concrete applications of the individual areas of the architecture system are stored in a repository, which is essentially interpreted as a database.

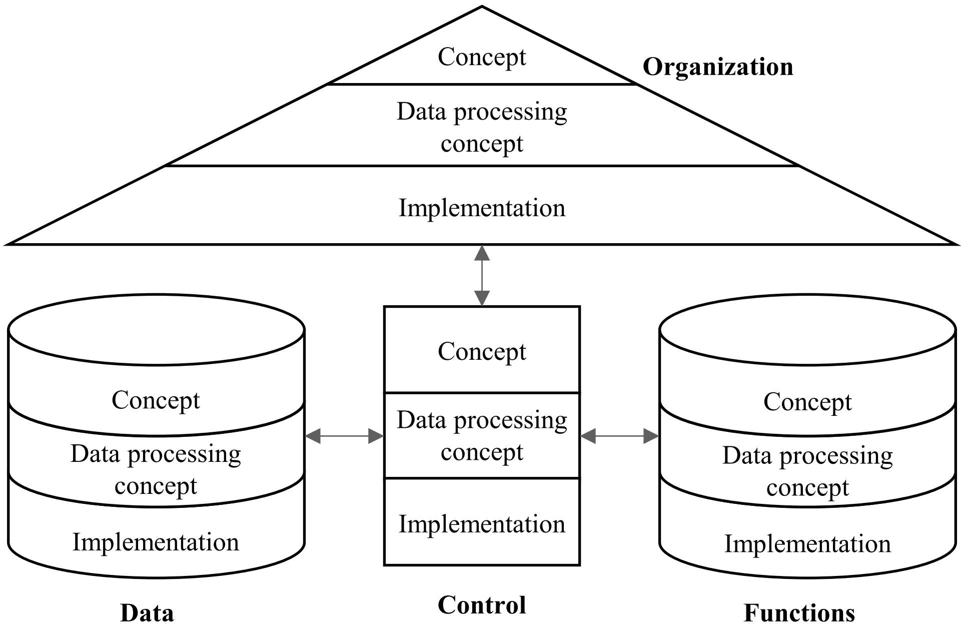



Figure 2.15: Architecture of integrated information systems (ARIS) (Scheer, 1998, p. 18)

The concept of ISAs as laid out in this section will be applied later in this thesis.

### 2.2.4 Information and communication technology

In business informatics, alongside the integrated consideration of economic and information science questions, there is a significant interface for exploring technical aspects (Mertens et al., 2017, p. 5). The German philosopher Günter Ropohl defines technique ("Technik") as: "(a) the set of utility-oriented, artificial, tangible entities (artifacts or material systems), (b) the set of human actions and arrangements through which material systems are created, and (c) the set of human actions in which material systems are used" (Ropohl, 2009, p. 31). In contrast, technology ("Technologie") refers to the scientific and systematic study of technique and is considered synonymous with the term engineering science ("Technikwissenschaft") (Ropohl, 2009, pp. 31–32).

In practice, the terms are often used interchangeably, particularly in English. Despite technique being the more accurate term according to these definitions when discussing information systems, this thesis will use the term technology throughout, as it is more commonly understood.

Information systems were also referred to as information and communication systems in section 2.2.3. For this reason, Krcmar (2015, p. 24) uses the term "information and communication technology" (ICT) for the underlying technology. ICT "is the totality of [technical] resources available for storage, processing, and communication, as well as the way in which these resources are organized" (Krcmar, 2015, p. 24). The frequently used abbreviation "IT" stands for "Information Technology". This has also become widespread in German-speaking countries and is used relatively widely for topics related to information processing. In the following, the abbreviation "ICT" is used to describe technical components and services in information systems for more precise specification.

The technical foundation of information systems is constituted by infrastructure. The technical side can be divided into hardware, software, and structural facilities that contain hardware components, among others. Basic technology refers to fundamental forms of ICT for implementing a technical infrastructure (Krcmar, 2015, p. 24).

ICT for information systems can be categorized using layer architectures or by assigning it to functional areas. Specifically, ICT solutions can be grouped based on their primary purpose: processing, storing, or communicating data and information. However, overlaps between these categories exist (Krcmar, 2015, p. 317).

### 2.2.5 Holistic information management

So far, the characteristic features and components of information systems have been explained. It becomes evident that designing, developing, and managing information systems involves numerous cross-disciplinary and specific tasks for both users and creators. Business informatics examines these tasks to generate insights for information management. The term 'management', which has various meanings in economic literature, can be understood here in a simplified way as the set of function-related leadership tasks for decision-making (Krcmar, 2015, p. 25). Accordingly, information life cycle management includes the strategic, tactical, and operational control of information systems (Alpar et al., 2019, p. 47).

Krcmar (2015, p. 107) takes one step further in his model of holistic information management by formulating four core areas of information management: The model includes, on the one hand, a structure of three levels, which are divided according to their proximity to technology, and, on the other hand, a component with accruing management tasks. The boundaries of the areas are defined as follows:

- Management of the information life cycle (level 1): refers to the management of the supply, demand, and use of information
- Management of information systems (level 2): refers to the design and application of information systems in a narrower sense, including the organization of data and processes
- Management of ICT (level 3): refers to the organization of technical resources and, in particular, the ICT infrastructure, including its functions
- Management tasks: refer to cross-level management tasks in the sense of business management, such as tasks in the areas of strategy, human resources or controlling (Krcmar, 2015, pp. 107–108).

Information life cycle management refers to the processes for controlling and coordinating "information" as a property within defined system boundaries. The aim is to provide decision makers with information effectively and efficiently (Picot & Reichwald, 1990, p. 264). The so-called "life cycle model of information management" attempts to take these aspects into account and to place them in a functional relation (Figure 2.16).

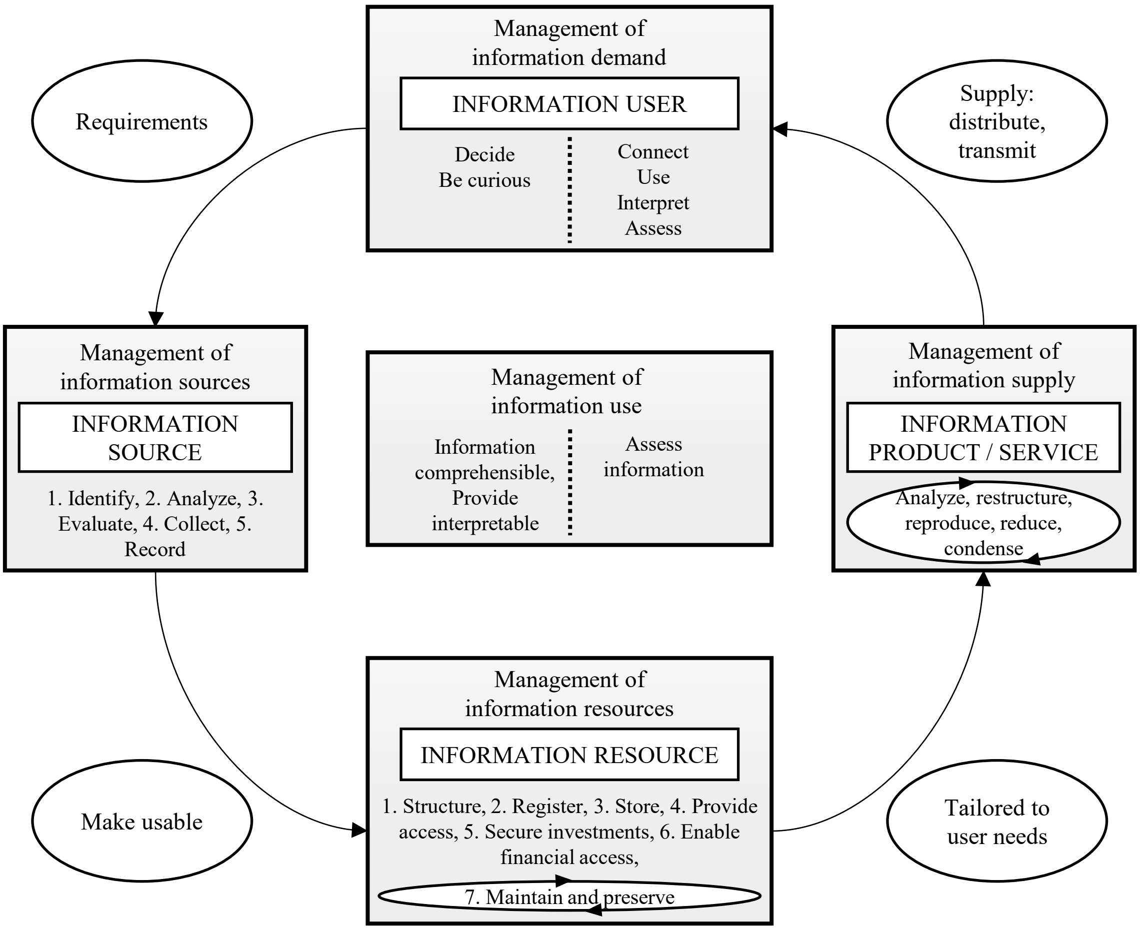



Figure 2.16: Life cycle model of information management based on Krcmar (2015, p. 119)

Particular challenges in information life cycle management exist in the determination of demand, need, and supply of information as well as in ensuring information quality.

## 2.3 Information modeling

The development, use, and analysis of information systems is significantly supported by models. Models of information systems and their elements allow the actors involved to receive a simplified, abstract representation of a real-world entity. Since models and the process of modeling will play an important role in this thesis, this section introduces selected basics of information modeling including guiding principles (section 2.3.1) and approaches to the modeling of information systems (section 2.3.2), data (section 2.3.3), processes (section 2.3.4), and business implementations (section 2.3.5).

### 2.3.1 Guiding principles

According to Stachowiak (1973), who is regarded as a pioneer in modern modeling theory, a model is a shortened representation of a physical or artificial original that serves a specific purpose for a specific subject within a specific period of time. This definition is based on the idea that the real-world entity is modeled with the help of a mapping relation. Another interpretation exists that regards a model as the result of a design process in which the model creator and users are involved (vom Brocke, 2015, p. 12). Models are considered subject-relative, purpose-relative, and perspective which means that they are based on the decisions, preferences, and perspective of the model creator (Steinmüller, 1993 as cited in Krcmar, 2015, p. 32). Other important characteristics of models are their function to partitioning of complex issues into subproblems and their level of abstraction by leaving out details and focusing on relevant aspects (Hansen et al., 2019, p. 133). In general, models can be classified according to type, form, reference object, scope of validity, content, purpose, and temporal phase (Krcmar, 2015, p. 35).

Modeling deals with the design and execution of processes related to the construction of models (vom Brocke, 2015, p. 25). For this, formal or rather informal methods can be applied. Usually, a notation is chosen that is formalized through a modeling language and that meets the specific requirements of a use case. Specific modeling languages relevant for information system modeling are explained in the following sections.

In order to ensure the quality of modeling, several guiding principles evolved in the literature (Table 2.5). This includes objectives that are used to assess the quality of the model and modeling conventions which serve as guidelines during the modeling process (J. Becker et al., 2012, p. 31).

Table 2.5: Guiding principles for modeling based on J. Becker et al. (2012, pp. 32–36) and Hansen et al. (2019, p. 141)

| Principle | Description |
|---|---|
| Correctness | This includes the syntactical (compliance to rules of the modeling language) and semantic (model is regarded as meaningful and purposeful by domain experts) correctness. |
| Relevance | Only relevant aspects should be modeled according to the defined goals. |
| Economic efficiency | The goals of modeling should be achieved with an appropriate relation of costs and benefits. This affects choosing the level of detail. |
| Clarity | A model should be designed in a legible, illustrative, and easy-to-understand way. |
| Comparability | It must be ensured that model and real-world entity as well as model and other models are comparable to each other. |
| Systematic design | The model should be constituted by meaningful elements and perspectives. |

In addition to guiding principles for the modeling process, there are attributes to assess the quality of an existing model. Krogstie (2012, p. 205) proposes a semantic quality framework (SEQUAL) consisting of different dimensions, such as the physical, empirical, syntactic, semantic, pragmatic, social, and deontic quality. These dimensions can be used to assess the appropriateness of a modeling language and to derive specific modeling techniques (Krogstie, 2012, pp. 241–242).

## 2.3.2 Information system modeling

Information system modeling refers to the modeling of the overall structure or of single elements of an information system. An information system model, also called information model in short, is thus an explicit model with information systems as the object of consideration (vom Brocke, 2015, p. 29). Information system models have traditionally been an important aspect in information system development and implementation due to their complex, open, and multi-element character. Several functions are connected to information system models:

- Derivation of requirements for their development process
- Assistance of understanding the system functionality
- Analysis of current and future states of the real-world entity, e.g. through simulation, and provision of a decision-making basis
- Basis for communication between humans and machines
- Basis for efficient management of a system and controlling of inputs and outputs (Krogstie, 2012, pp. 11–12)

According to Falkenberg et al. (1998, p. 54), model representations of information systems must account for multiple semiotic levels, structured in a ladder from technical to social aspects. This framework highlights the interrelation between physical media, modeling languages, meaning, and social context, emphasizing that information systems are not purely technical constructs but embedded in human interpretation and organizational structures (Figure 2.17).

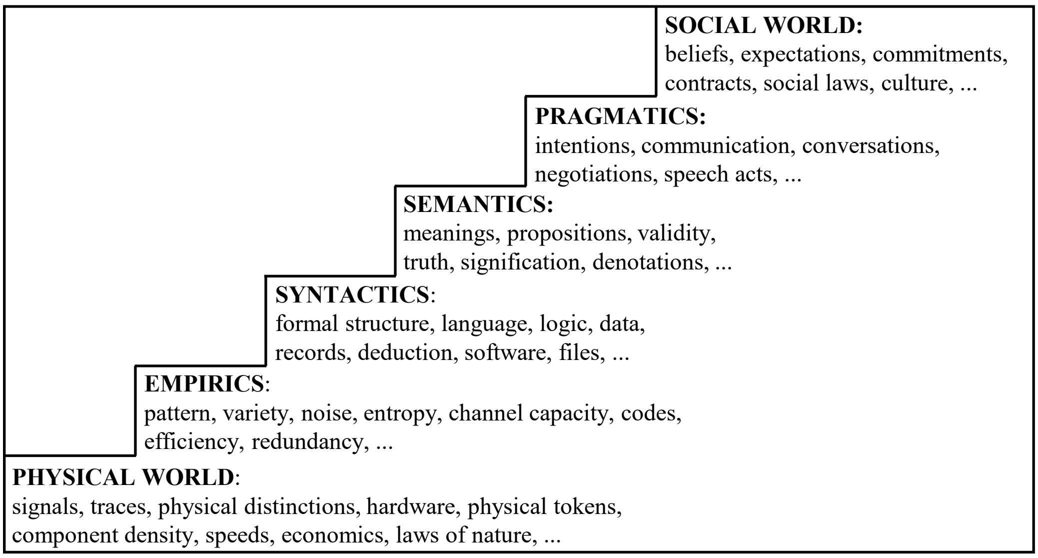



Figure 2.17: The "semiotic ladder" between the "physical" and the "social world" (Falkenberg et al., 1998, p. 54)

The modeling process for information systems is sometimes interpreted as a form of conceptual modeling. Conceptual models describe phenomena in a specific domain, such as states, processes, entities, and objects, at a certain level of detail. For information systems, conceptual models can be developed for the different elements, such as the data, processes, and organizational aspects (Krogstie, 2012, pp. 1–2).

Different types of information system models can be distinguished:

- Architecture models define the system's structure, boundaries, inputs, and outputs. They provide multiple perspectives and serve as a foundation for system design. Sunyaev (2020, pp. 28–34) formulates nine principles for creating and modeling ISAs (section A.2.1).
- Time-based models represent past, present, or future states of a system (Hansen et al., 2019, p. 134).
- Systemic models highlight interrelationships between systems. Since models and reality influence each other, findings may not always be directly transferable (Krcmar, 2015, pp. 32–33).
- Metamodels describe how models are created. They can define the modeling language (language-based metamodels) or the modeling process (process-based metamodels). Further meta levels can be added, forming a hierarchy (Krogstie, 2012, p. 101; Strahringer, 1998, pp. 3–4).
- Reference models serve as templates for model development. Standard-similar reference models enable cost-efficient model creation but may reduce company-specific competitive advantages (J. Becker et al., 2012, p. 34; Krcmar, 2015, p. 41; vom Brocke, 2015, pp. 31–32).

Selected types of information system models will be referenced later in this thesis.

### 2.3.3 Data modeling

Data are essential to information systems. Data models represent a simplified representation of their real-world equivalent. Data can be modeled according to their proximity to technical implementation. There are semantic/conceptual, logical, and physical approaches to data modeling. Physical models are strongly oriented towards the actual technical form of data, while semantic and logical approaches are closer to the real world (Baars & Kemper, 2021, p. 54).

In times of rapid growing amounts of digital data and increased connectivity, semantic modeling becomes more and more relevant. The necessity for semantic data models follows the inability of logical models, such as relational, network, and hierarchical approaches, to satisfy the need for meaningful conceptual models since they are biased towards a specific database type and limited in scope (Peckham & Maryanski, 1988, p. 153). Semantic data models, although present since several decades, regained popularity within the last years because of their relevance for linked data and semantic web technology as well as for artificial intelligence (Alexopoulos, 2020, p. xi).

Concepts that are frequently mentioned alongside semantic data modeling are taxonomies, ontologies, and data dictionaries.

- A taxonomy provides a formalization mechanism to classify terms and their relations. It can be visualized in a tree structure.
- Ontologies specify a concept in a domain by defining the relevant entities and their relations. They usually go beyond a taxonomy because they are more sophisticated in the definition of contents and entities.
- A data dictionary is a repository that provides metadata about a data specification, such as an ontology, by defining all relevant terms and formats (Costin et al., 2022, pp. 11–12).

For the formal development and representation of data models, specific modeling languages are applied. Modeling languages are artificial languages usually represented in graphical or text form. They are differently detailed and rigid in their syntactical rule set. They also differ depending on their main perspective which leads to various structuring principles. This includes, for example, a focus on behavioral, functional, structural, object, or communicational aspects. In addition, modeling languages can be distinguished according to their perspective on time. They can take in an either static or dynamic perspective and a temporal or full-time perspective (Krogstie, 2012, pp. 107–109).

In order to develop high quality models, a model creator must choose a suitable modeling language. A selection of relevant data modeling languages is provided in Table 2.7, comparing their modeling principles, strengths, and weaknesses, with a focus on semantic approaches due to their relevance for early-stage conceptual modeling. Each language has distinct features, strengths, and limitations, making them suitable for different use cases.

Table 2.6: Comparison of data modeling languages including their modeling principle, strengths, and weaknesses based on (Bergman, 2009; Bonduel et al., 2022; Karagiannis et al., 2016; Peckham & Maryanski, 1988; Sacks et al., 2018)

| Language/approach | Main modeling principle | Strengths | Weaknesses |
|---|---|---|---|
| Entity-relationship-model (ERM) | Combination of entities, attributes, and relationships using several abstraction mechanisms | Ease of understanding and visual representation<br>Easy to transform into relational database model | Difficult to scale<br>No representation of data manipulation<br>Limited relationship representation |
| Unified modeling language (UML) class diagrams | Object-oriented modeling based on standardized graphical language | Interoperability with other UML diagrams<br>Standard constraint definition language | Complexity of object-oriented approaches<br>Complexity of larger models |
| XML schema definition (XSD) language | Description and validation of elements in XML documents | Based on XML and thus human- and machine-readable | No graphical illustration<br>Complexity of the language |

| | | | |
|---|---|---|---|
| | | Contains metadata and self-explaining | Difficult to use for unstructured content |
| EXPRESS language | Declarative, object-oriented modeling language for product data | Standardized through ISO<br>Machine-readable<br>Original basis for Industry Foundation classes (IFC) data schema (section X.X) | Difficult to understand for non-experts |
| Resource description framework (RDF) | Combination of subjects, predicates, and objects to create atomic triples<br>Basis for ontology-based modeling and more specific ontology languages | Notation and storage through several RDF serializations<br>Application with linked data and semantic web technology through open-world-assumption<br>Enables interoperability between data formats | Limited ability to validate documents<br>Complexity to search information<br>Objects can only be linked through triples |

Selected data modeling languages are referred to later in this thesis as required.

### 2.3.4 Process modeling

Understanding the processes that coordinate all the different entities of an information system is crucial for their successful use. In general, processes transform inputs to outputs by carrying out specific functions (Krcmar, 2015, p. 58). The literature predominantly investigates process modeling for the sake of business processes. The diversity of processes in a business environment and in other domains is infinite and heavily depends on the object of consideration and the framework conditions (Gadatsch, 2020, p. 5). The typical aim is to analyze processes in their current and future state to identify potentials for improvement (Krogstie, 2012, p. 63). Processes can be classified according to their relative importance resulting in core processes and support processes (Gadatsch, 2020, p. 8).

In information management, a typical distinction can be made between the life cycle stages of data. This involves processes of data creation, editing, and distribution, for example. The exact boundaries between a process and a function are not always clear, since a specific function can be an integral part of a process, but it can also include an internal process itself. Thus, determining the level of abstraction has a big influence in process modeling. For simplification, functions can be regarded as individual building blocks that contain a certain task while a process combines these blocks in a sequence of actions (Gadatsch, 2020, p. 16; Scheer, 1998, p. 8).

Several methods and languages exist that facilitate the modeling of processes, such as the business process modeling language (BPMN), enhanced event-driven business chains (eEPCs), petri nets, and UML activity diagrams. These languages are compared in Table 2.7 against their main modeling principle and their most relevant strengths and weaknesses. All process modeling languages have specific characteristics, coming from different traditions, focusing on different aspects, and being appropriate for various domains (Farshidi et al., 2023). This makes it difficult to choose the language that is most suitable for the specific use case. The SEQUAL framework by Krogstie (2012, pp. 287–290) can provide first guidance to evaluate the quality of process models. Above that, several publications deal with the question of how to choose an appropriate process modeling language including Pereira and Silva (2016), Awadid et al. (2017), and Farshidi et al. (2023). Farshidi et al. (2023) found that BPMN offers the greatest functionality of more than 20 compared languages and that it is the most suitable language in several case studies based on the individual requirements. These results go in hand with the ones from Pereira and Silva (2016, p. 623), who compared several languages against a framework of quality characteristics. Still, it is important to choose a modeling language carefully according to the specific requirements.

Table 2.7: Comparison of process modeling languages including their modeling principle, strengths, and weaknesses based on (Farshidi et al., 2023; Gadatsch, 2020; Gebretsadik, 2020; Scheer, 1998)

| Modeling language | Main modeling principle | Strengths | Weaknesses |
|---|---|---|---|
| Business process modeling language (BPMN) | Combination of different elements, such as flow elements, activities, events, messages, and data, to graphically represent business processes | Expressive modeling through precise notation options<br>Easy to understand without prior knowledge for simple models | Strong focus on business processes<br>Effort to learn and understand more specific notations |
| Enhanced event-driven process chain (eEPC) | Using events, functions, and connecting operators for process modeling | Simple and easy to understand without prior knowledge<br>Integrates perspectives on information systems | No universal syntax since not standardized<br>Limited expressiveness |
| Petri nets | Combination of places, transitions, and arcs to visualize and simulate a process | Based on mathematical definition for semantics and mathematical theory for analysis | Complex semantics and difficulty to model complex problems |

| | | | |
|---|---|---|---|
| UML activity diagram | Object-oriented modeling of workflows | Interoperability with other UML diagrams<br>Applicable for various use cases | Interactions between objects are not well specified<br>Difficult to model complex processes |

Based on these insights, a suitable process modeling language will be applied later in this thesis.

### 2.3.5 Business modeling

Information systems are often an integral part of a commercial product or service. These products or services are developed and implemented by organizations, also just called 'businesses' when originating from the private sector in an economy. Businesses, but also other organizations that develop, manage, and sell information systems, are in need of suitable business models.

A business model is an idealized and aggregated representation of how organizations create, deliver, and capture value. As part of a business strategy, its main function is to provide a holistic overview on the main building blocks of a business. It can be a helpful tool throughout the whole life cycle of a business innovation including its design, development, and implementation. At a very early stage, a business model helps actors to evaluate the potential success of a business idea and to consider all relevant aspects. This can benefit entrepreneurs as well as established organizations that look for a business model innovation. A business model can help organizations in the strategic positioning of products/services. It also can be used for continuous evaluation and improvement as well as for effective communication of a business idea (Fielt, 2013, pp. 87–88; Shafer et al., 2005, pp. 202–204; Teece, 2010, pp. 173–186).

Structured approaches to business model innovation are more popular than ever before. Especially, startups, who are confronted with high uncertainty and turbulence in a dynamic market environment, rely on structured business models in their endeavor for future success. Within the last 20 years, several tools and frameworks were developed for this reason. One of the most popular frameworks is the 'Business Model Canvas' (BMC), which functions as a form consisting of nine building blocks that business innovators can fill in (Figure 2.18). The strengths of the BMC lie in the compact overview, the focus on value creation and customers as well as the implied relationships between the building blocks (Gründerplattform, 2025).

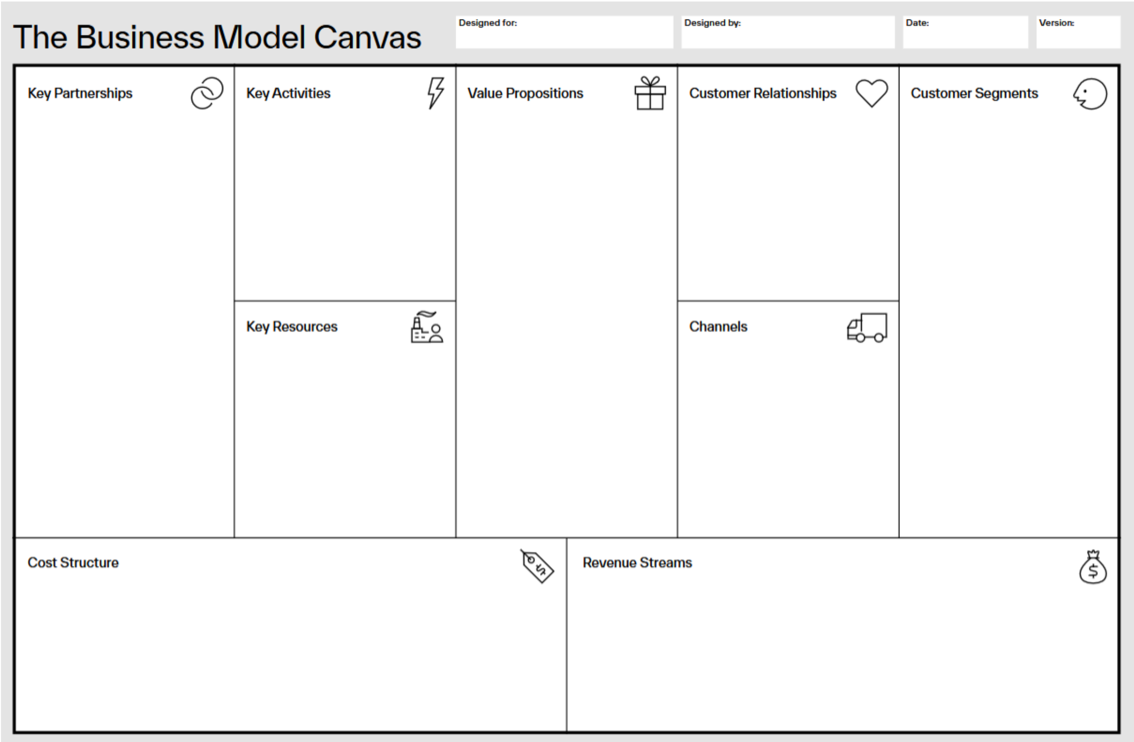



Figure 2.18: Visualization of the business model canvas (Strategyzer, 2025)

The building blocks in a BMC all have their specific meaning for a business model. Innovators need to answer specific questions to fill in the form (section A.2.2).

Despite its popularity, the BMC also has some limitations. For example, it does not mention the specific purpose of a business. It also does not take aspects of the market environment into account. For a complete business strategy, additional tools need to be considered, such as a business plan or an industry analysis (M. Becker & Bröcker, 2021, pp. 5–6). Various but often less popular alternatives exist (Fielt, 2013, p. 94).

## 2.4 Information systems for real estate management

The real estate industry increasingly implements information systems for its use cases. These systems take in various roles with regard to the complexity and specificity of real estate. Lately, information systems that are directly linked to managing buildings throughout their life cycle are gaining popularity. They can be subsumed under the group of building information systems (BISs). For a better understanding of BISs, an initial definition is given in section 2.4.1. The newly gained attention of BISs is a result of several drivers, such as digitization, new information needs, and sustainability requirements (section 2.4.2). A brief overview of the associated literature is given in section 2.4.3, reinforcing the identified research gap.

### 2.4.1 Definition of building information systems

The term "building information system" is built on the merge between a "building" and an "information system". Thus, a BIS can be understood as an information system, specifically designed for a building as the object of consideration. Based on the simple breakdown of the term, its meaning still stays rather unclear. This has to do with the various tasks throughout the building life cycle and the specific information systems that may be designed for these tasks. For this reason, no common understanding has yet been established. This also reflects in differing interpretations within the literature (Table 2.8).

Table 2.8: Definitions for Building Information Systems

| Source | Interpretation of a BIS as a(n)… |
|---|---|
| Magnet (1989, p. 76) | inviolable, open, flexible, and automated system for building automation and security |
| Terai and Kaneko (1990, p. 169) | Advanced construction technology (ACT) system that sets the frame for information processing throughout the life cycle of buildings |
| Kis Papp (1999, p. 31) | system for collection, documentations, and evaluation of building information consisting of a data model, software, hardware, and systemic functions |
| Lützkendorf and Speer (2005, pp. 182–194) | Knowledge base throughout the building life cycle to satisfy the information needs of different actors and to provide a basis for the assessment of object performance and quality |
| Paul (2007, p. 591) | Database for geometric information in conjunction with building information modeling (BIM) |
| Vanlande et al. (2008, p. 71) | Internet platform to merge geometric and other information throughout the life cycle of buildings and to visualizing of 3D models |
| Rohde et al. (2011, pp. 82–88) | Dynamic collection of building-related data and documents throughout the building life cycle |
| Varoudis and Patlakas (2014, p. 505) | Distributed system based on a cloud architecture to enable building-related information management and to overcome deficiencies of BIM |

There is not much evidence on the use of the term "building information system" in academics. The overall meaning stays vague. Therefore, a new definition was developed based on interpreting previous understandings and by considering the underlying nature of buildings and information systems:

*A building information system (BIS) is a human-machine-interrelated system that supports building owners and other actors involved in managing building-related information by facilitating the collection, storage, sharing, and use of building-related data.*

This definition stresses the relevance of information management and the delimitation to buildings. Still, it allows for a specification in different use cases. For this reason, a BIS can also be understood as a more general concept that illustrates the character of many systems and tools in place. the definition given is the basis for the further understanding of BISs in the thesis.

### 2.4.2 Drivers for the development of building information systems

The increasing popularity of BISs is a result of several drivers, such as global megatrends and trends of information management in the real estate industry. As already outlined in the introduction, these developments influence the industry in various ways. These drivers act to varying extends over the course of years and decades. Megatrends, such as the need for sustainability, the shift in social values, and the increasing level of regulation apply pressure on the actors of the real estate industry and lead to needs of action (Worschech & Lützkendorf, 2022, p. 2). Actors must react by analyzing the implications of megatrends on their immediate environment (Pfnür & Wagner, 2018, pp. 9–10). BISs can be regarded as both an answer to handle the consequences of trends and a result of new possibilities, such as technological advancements. The following drivers could be identified that significantly impact the newly and further development of BISs (Buchholz & Lützkendorf, 2022a, pp. 2–3):

- Tradition to store building-related data and documents
- Need for more transparency
- Changing information needs
- Sustainability
- Digitization
- Globalization

The evolution of BISs and the systematization of building-related data is strongly connected with the establishment of *traditions to store building-related data and documents*. While architechtural plans were destroyed in the Middle Ages, builders and building owners started to keep these documents beyond the construction stage in the $19^{th}$ and $20^{th}$ century. This development was partly also a result of building regulations and the obligated handover of construction records (Knobloch, 2017). Throughout the $19^{th}$ and $20^{th}$ century, the construction industry experienced significant economic growth, technological improvements, increase in professionalism, and reduction of fragmentation as historically documented for the UK (Holt, 2015, pp. 263–266). These developments were one of the reasons why building-related information became more widely available. Innovations and new business models increasingly involve information systems today, since building-related information has been fragmented or not available at all in traditional real estate management practices, new forms of contracting allow for a better-organized information exchange process, and actors follow more proactive strategies in managing their building stock (Talamo & Bonanomi, 2015, p. 106).

The real estate industry is traditionally characterized by information asymmetries and insufficient information overall (Lorenz & Lützkendorf, 2008). This leads to a *lack of transparency* and undesirable phenomena, such as adverse selection of moral hazard (section 3.4.5).

Representatives of the real estate industry try to overcome this lack of transparency by developing new approaches for information management which explicitly include the implementation of BISs. One example for this is given by the introduction of energy performance certificates (EPCs) in the EU. Their main function is to signal information about the energy performance of buildings so that buyer and seller have the same level of information in a property transaction. This goal of increased transparency has been formally introduced in European regulation within the 'Directive 93/76/EEC to limit carbon dioxide emissions by improving energy efficiency' (SAVE, 1993, p. 28) and since then has been considered as an additional aim in other directives and regulations.

As stated, the construction and real estate industry is constantly evolving under the external pressure induced by megatrends on the specific actors. The economic pressure on market participants is one factor that is present since the very beginning. The need for profitable investments and the capital intensity of real estate both drove the establishment of various forms of developing, owning, and using a building. Therefore, especially actors from the return-oriented perspective are obliged to manage their building stock effectively and efficiently. In this task actors experience *changing information needs* over time based on changing framework conditions and changing objectives. In general, the information density for managing buildings throughout their life cycle increased significantly within the last decades based on new forms of data collection, storage, and distribution. This led, for example, to proposals on how to improve knowledge retention and management in construction firms (Schaefer, 1993, p. 187). At the same time, the introduction of information systems for real estate portfolio management has been discussed for a while (Fransson & Nelson, 2000, p. 154). Barkley (2001, p. 161) specifically identifies the need for performance data in portfolio management, expressed through key performance indicators (KPIs), as a driver for information system development.

The need for a more *sustainable built environment* is one of the most influential megatrends within the real estate industry today. The actors involved in the building life cycle need data about the past, present, and future state and performance of a building to make informed decisions (Lützkendorf & Lorenz, 2014, p. 6). The real estate industry tackles this challenge by developing BISs that are specifically designed to document, assess, and communicate the environmental performance of buildings. Thus, they serve to reduce the complexity of adapting to requirements of sustainable development (Lorenz & Lützkendorf, 2008). In addition, methods and technologies, such as BIM applications and life cycle assessment (LCA) approaches, are further developed to provide decision support in designing, constructing, and operating buildings more sustainably.

In an empirical study, Pfnür and Wagner (2018, pp. 48–57) found that actors of the German real estate industry regard *digitization* and a consistent data and information exchange as key solutions to cope with new requirements induced by megatrends. Thus, digital solutions provided by BISs are increasingly demanded for all tasks throughout the building life cycle. On the other hand, digitization has a strong push effect on the real estate industry by enabling innovations, new business models, and more effective, more efficient, and automated ways to handle traditional tasks. Digitization is mainly a result of advancements in ICT to which the real estate industry constantly adapts. This is reflected in newly and further developed BISs. Early evidence comes from Magnet (1989, p. 76), who proposes a building information system functioning as a fire detection system that extends to other aspects of building automation. The proposal includes a description of system-related requirements, actors involved, primary functionalities, and a model for visualization (Magnet, 1989, pp. 74–78). In the mid-90s, information systems were, also in the construction process, regarded as a means of digitalization with great influence (Kelly et al., 1997, p. 17).

The evolution of BISs is also driven by *globalization*. Globalization is an ongoing process that permeates all aspects of life and leads to a multidimensional linkage on a global level (Pohl & Vornholz, 2016, p. 7). This leads to transactions beyond traditional real estate submarkets and thus reinforces the need for reliable information on foreign properties and markets (Ganter & Lützkendorf, 2019, p. 4). In addition, globalization goes along with an increased mobility of people which results in a more fluctuating demand for properties, buildings, and rental spaces (Pohl & Vornholz, 2016, p. 8). The increased use of BISs supports building owners and other actors involved in real estate management in handling the consequences of globalization.

### 2.4.3 State of research

The design, development, and application of BISs has been examined throughout the last decades forming several research areas with a specific scope. The knowledge in this domain derives from basics in building-related information management and from proposals regarding the specified use of information systems. The findings from research usually show significance for practical implementation, but do not always represent the latest developments from the industry. Within the last years, a convergence of academia, industry, and public sector becomes evitable. In the following, the focus lies on findings from research.

Based on their function as an information system, as defined in section 2.4.1, BISs build on information management principles for the building life cycle. However, few publications draw their reasoning for the structure and functionality of a BIS out of information management insights. Mehlis (2005), for example, systematically analyzes the basics regarding the collection, supply, and demand of building-related data. He uses this information for the development of a calculation model that evaluates the costs of data collection and storage. Within his analysis, he defines a real estate information system as a tool to holistically manage information that is relevant for real estate management (Mehlis, 2005, p. 135).

Lützkendorf and Speer (2005) investigate the reasons for the lack of transparency in the real estate market and evaluate the need of building-related data to signaling building quality and performance. They propose the use of BISs as a life-cycle-accompanying tool to manage building-related data and make suggestions on their structure (Lützkendorf & Speer, 2005, pp. 190–191).

Lorenz and Lützkendorf (2008) analyze the implications of sustainable building on property values. For this, they elaborate basics for the composition of property values and for the information management of actors of the real estate industry. As a result, they emphasize the function of building passports/files as information containers throughout the life cycle of buildings and, above that, identify a bunch of tools and information systems for quality assurance and decision support (Lorenz & Lützkendorf, 2008).

Rohde et al. (2011) identify the information needs of actors of the real estate industry in various occasions and tasks by analyzing documents for data collection from practice, such as documentation guidelines, due diligence checklists, rent indexes, valuation methods, assurance checklists, and related standards. In addition, the authors carried out expert interviews and workshops. Against the background of existing basics and approaches for systematization of building-related data, they come up with an own proposal for a BIS that includes the life-cycle-accompanying management of static and dynamic information as well as the ad hoc generation of relevant documents. According to the authors, their proposal can serve as a basis for practical implementations (Rohde et al., 2011, pp. 84–88).

Talamo and Bonanomi (2015) dedicate a whole book to information management and information systems within the real estate industry with a focus on use cases in facility management. They systematically identify the information demand in facility management and put this into the context of implementing KPIs. In addition, they propose a job-sharing approach of different tools, calling them inventory, building registry, information system, and command center, to manage information for facility management. For each of these tools, they explain their functionality in detail. They also investigate the use of BIM for facility management.

Additional to publications that explicitly interlink information management basics with BISs, there is a greater number of publications that transfer the term and concept of information systems to use cases in real estate management. Due to the various potential use cases and the lacking standardization of the term, the amount of relevant literature remains unspecified. A brief overview is given on selected examples.

Gessmann (2008) makes a proposal for an internet-based building data repository that should work as a lifecycle-oriented integration platform. He builds his work on the concept of room books to combine alphanumeric and geometric data to describe a building's structure (Gessmann, 2008, p. 43). His goal is to develop a tool that enables the continuous maintenance of building-related information (Gessmann, 2008, p. 89). He developed a prototype to demonstrate his proposal.

Pfnür (2011, pp. 421–422) interprets a real estate information system as a system that supplies an organization with building-related data according to its needs. He regards such a system as the linkage between ICT and business administrative processes. It should facilitate the collection, storage, and supply of building-related data and thus needs to fulfill several requirements in terms of its structure, functionality, use, and economic efficiency, for example.

Nebauer (2012, p. 50) makes a proposal for a real estate information supply system that works in the context of controlling as a linkage between specific controlling systems and overall performance and risk controlling for institutional real estate investors. The goal lies in the harmonization of building-related information to centrally manage the data coming from project development, maintenance, and risk controlling systems for example. In addition to explaining the basic structure and functionality, Nebauer (2012, pp. 52–58) briefly defines requirements of information management on the system.

Treleaven et al. (2021, p. 445) outline the concept of a real estate data marketplace that supports the structured exchange and validation of building-related data across the life cycle. Their proposal emphasizes the role of digital technologies in enabling more transparent and efficient information flows and introduces a governance framework for managing data access and quality. While not explicitly framed as a BIS, the marketplace functions as a comprehensive information system supporting tasks such as planning, management, and compliance, and reflects the increasing relevance of integrated data environments in real estate practice (Treleaven et al., 2021, pp. 456–461).

It becomes clear that the idea for BISs already exists for quite some time. Still, the evidence in the literature remains fragmented and not well connected. As of late, new terms and concepts evolve that partly build on already existing initiatives or technologies and that take over functions as BISs. This includes passports, logbooks, and similar concepts as well as virtual building models based on BIM applications or digital twins. Although there are various types of information systems for more or less the entirety of tasks throughout the building life cycle including the return-oriented, performance, and user perspective (section 2.1.4), above mentioned BISs from the group of passports etc. receive more attention today. This has to do with their broader scope which is increasingly demanded against the background of several drivers (section 2.4.2).

The developments in this research domain are very dynamic. van Capelleveen et al. (2023) are one of the first to provide an overview on systems that use the term “passport”. At the same time, there is a strong interest from the EC in the development of so-called digital building logbooks. This interest was initiated with several research projects around 2016 and continues still through various initiatives and research projects. In addition, current research focuses on BIM and digital twins as the solution to digitize the complete value chain.

Despite all new concepts and initiatives, the literature is still lacking a conceptual basis of information management throughout the building life cycle that these concepts build upon. The findings of this initial review can be summarized as follows:

- Information management throughout the building life cycle is rarely well defined in the literature and rather stays a vague concept despite its huge relevance for the effectivity and efficiency of building-related tasks.
- Few publications ground their proposals of BISs and similar tools on basics of information management. This is, in conjunction with historical developments, one of the reasons, BISs are often developed specifically for one purpose which contributes to the diversity of approaches and which prevented the development of a holistic BIS (Rohde et al., 2011, p. 85).
- The missing standardization of terms adds to the fragmentation of knowledge. In addition, the object of consideration and the system boundaries are often not specified. Thus, company-specific and company-independent approaches are mentioned interchangeably.
- New concepts, such as passports or logbooks as well as further developed technologies, such as BIM and digital twins, increase the variety of BIS approaches.
- Researchers reasonably explore and discuss new possibilities from digitalization. Their proposals with regard to BISs, however, rarely consider the information demand of actors and their related requirements. In addition, the combination of different ICTs for BISs stays mostly unexplored.

The identified insufficiencies emphasize the need for a systematic approach that thoroughly analyzes the basic principles and problems of information management and the new opportunities through technological advancements to translate these insights into requirements on a BIS. Especially, the need for a BIS that facilitates the life-cycle-accompanying storage and management of building-related data becomes evident reinforcing the relevance of the research gap posed in section 1.3.

## 2.5 Summary of basics

Chapter 2 introduced fundamental concepts essential for understanding the subsequent analysis and results chapters. It covered:

- Real estate management: Defining real estate and buildings, identifying key actors in the industry, outlining the building life cycle, and discussing associated tasks. These aspects form the foundation for further discussions on building-related information management and data.
- Information management: Introducing key terms and concepts from business informatics, including data, data sharing, information systems, ICT, and the role of information management. This serves as a basis for analyzing technologies and developing the requirement profile for BISs, as well as for the proposals presented in the results chapter.
- Information modeling: Providing an overview of relevant modeling techniques that will be applied in the results chapter.
- Information systems for real estate management: Integrating the concepts of information systems with real estate and buildings, offering an initial definition of BISs, outlining the factors driving their development, and reviewing how the topic has been addressed in academic literature. This contributed to reinforcing the research gap of this thesis.

The concepts and definitions introduced in this chapter are assumed as prior knowledge in later sections and are referenced where appropriate.

# II Identification and analysis of requirements for building information systems

# 3 Information management throughout the building life cycle

*Effective information management is crucial for supporting decision-making and collaboration across the building life cycle. Chapter 3 establishes the foundational understanding of building-related data, its management processes, and the challenges that actors face in leveraging these data effectively.*

*The chapter begins by defining the scope and categorizing the types of building-related data (section 3.1). This provides a clear framework for understanding how data aligns with tasks and decisions throughout the life cycle. Then data creation and collection processes are examined, emphasizing the diverse sources and methods involved (section 3.2). Next, the specific data needs of actors are analyzed, linking them to tasks across different life cycle stages (section 3.3). It highlights the complexity of managing these diverse requirements and the importance of aligning data content with actor demands. Additionally, recurring problems in information management, such as fragmented data, lack of interoperability, and inconsistent quality are investigated, which hinder effective decision-making and collaboration (section 3.4).*

*In chapter 3, the foundational principles from chapter 2 are built upon, additional key concepts are introduced, and targeted analyses are conducted based on this extended framework. The objective is to lay the groundwork for the development of a requirement profile for BISs in chapter 5.*

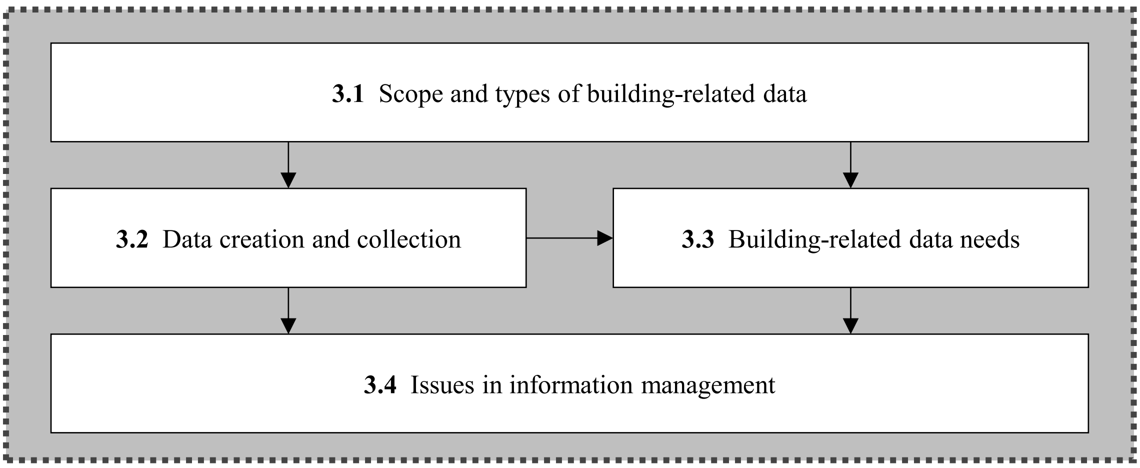



Figure 3.1: Structure of chapter 3

# 3.1 Scope and types of building-related data

In the course of the life cycle of a building, a large amount of data are generated. Within this section, a definition for “building-related data” is developed first (section 3.1.1). Second, options to classify building-related data according to distinguishing criteria are examined (section 3.1.2). Based on the understanding of building-related data, typical approaches for systemization from the real estate industry are explained. This includes classifying “building-related” based on quality characteristics of a building (section 3.1.3) and the determination of building attributes (section 3.1.4). The findings will help to stress the relevance of data in building-related information management and thus help to determine which data are needed in a holistic BIS.

## 3.1.1 What are building-related data?

Before analyzing the abundance and relevance of building-related data, it is necessary to clarify what falls under this concept. The literature lacks a standardized term, using various expressions such as “building data” (Hartenberger & Lorenz, 2017, p. 13), “building information” (Lützkendorf & Speer, 2005, p. 182), “property data” (Society of Property Researchers [gif], 2021, p. 33), “real estate data” (Mehlis, 2005, p. 1), “life cycle data” (Starzner et al., 2007, p. 12) etc. Some works avoid a specific term altogether, instead paraphrasing building-related data in different ways (Talamo & Bonanomi, 2015). However, none of these terms provides the precision required for this chapter:

- “Property” is ambiguous and primarily used in British English, making it unclear whether it includes only the plot or the constructed asset as well. Moreover, "property data" is often associated with object properties rather than the built asset itself.
- “Real estate data” could be appropriate, but it is frequently used in the context of market data rather than (single) buildings.
- “Building data” might be suitable, but in literature, "building" is often used as a verb, making the term imprecise.
- “Information” is generally suitable, but since it is a construct of human knowledge rather than a structured form bound to a medium, it does not provide the manageability required for information systems.
- “Life cycle data” introduces a relevant perspective but lacks explicit reference to buildings.

Due to these limitations, a more precise definition is derived based on the components of the term "building-related data" and is aligned with the contents of sections 2.1.1.1 and 2.2.1.1:

> *"Building-related data comprise all representations of real estate-related information that inherently exist in a structured form on a medium. They may follow predefined schemes, formats, or classifications and serve as a basis for information that actors can interpret. In a narrower sense, they provide information about buildings to relevant actors."*

From the term "building-related data" alone, it is not clear whether respective data refer to a single building, to a portfolio of buildings, or to real estate in general. The term “building” is preferred over other terms, since it is universally used around the globe and since it is most of the time used to refer to individual buildings. For the purpose of this thesis, the term “building” is used as a specification of real estate on single building level. In this respect, the term “building-related data” goes beyond the physical-technical dimension. It includes more than physical aspects, for example from the legal, economic, environmental, or social perspective, which will be evaluated in the following section.

### 3.1.2 Types of building-related data

The definition of real estate distinguishes between physical, legal, and economic aspects (section 2.1.1.1). The time component adds an additional dimension to the definition. On a data level, this leads to a differentiation of *static data*, which are unchanging in a certain period of observation, and *dynamic data*, which may be subject to change. In practice, it is not always trivial to distinguish between static and dynamic building-related data, as many data can be constant for a certain period of time, but change in the long term (Mehlis, 2005, pp. 50–51). It seems clear that all building-related data that are constant over the entire life cycle of a building should be classified as static. For dynamic data, appropriate thresholds are needed to determine whether the data are still static or already dynamic.

According to the specifications of GEFMA 400, static data include inventory data. They refer to the physical building structure or to specific building components and are available either in the form of alphanumeric or geometric data (Bartels, 2020, p. 39). Alphanumerically is the term used to describe data that are represented in the form of characters, digits, and symbols, such as key figures or descriptions. Geometric data are defined by its size, shape, dimensions and position. They are, for example, planning documents (DIN EN 17412-1:2021-06, p. 7).

Another category of building-related data includes master data. These are static and long-term data with a low frequency of change. The term has gained significance above all in the course of electronic data processing. In business informatics, ‘master data’ refer to the basic data of a company. In addition to their long-term nature, they are characterized by their relative independence from other data (Alpar et al., 2019, p. 206). In the case of buildings, this can include basic information about the owner or address, for example. Condition data are more dynamic and provide information about operating states of the installed building services or measured values of physical variables, for example. Consumption data provide information on the consumption of resources such as fresh water or energy (Turianskyj et al., 2018, p. 232). Table 3.1 provides an overview on the categories of building-related data that can typically be found in theory and practice.

Table 3.1: Categories of raw building-related data

| Data category | Definition |
| --- | --- |
| Master data | Static reference data that uniquely identify and classify core entities related to a building, such as its ownership, identifiers, typology, or categorization |
| Location data | Static and dynamic data on the physical environment of a building |
| Inventory data | Static data describing the designed or as-built state of a building and its elements |
| Condition data | Dynamic data capturing the actual condition of building components and services over time |
| Economic data | Dynamic data related to financial, tax, or valuation aspects |
| Legal data | Dynamic data involving property rights, contracts, and legislative requirements relevant throughout the building life cycle |
| Process data | Dynamic data on construction, management, and other building-related processes not covered in other categories |
| Consumption and emission data | Dynamic data on natural resource consumption (system input) and solid, liquid, and gaseous emissions (system output) from building-related processes |

With this structured classification of building-related data, it becomes clear that not all data related to the built environment qualify as building-related data. General market and economic data, such as real estate price indices or macroeconomic trends, do not fall into this category unless they specifically pertain to a building. Similarly, broad geographic or climate data are not considered building-related unless directly linked to a building's location or environmental impact. Personal or behavioral data, unless tied to building operations or management, also do not belong to this category. Additionally, abstract concepts like architectural principles or regulatory frameworks, as well as data from unrelated industries, are not building-related unless explicitly connected to a building, its life cycle, or its management.

So far, data was characterized based on selected criteria. In principle, there are several other ways to distinguish building-related data. (Table 3.2).

Table 3.2: Selection of criteria for distinguishing building-related data

| Criterion | Description |
|---|---|
| Static vs. Dynamic | Static data rarely change. Dynamic data update frequently or in real-time. |
| Alphanumeric vs. Geometric | Alphanumeric data are text or numbers. Geometric data represent shapes or spatial dimensions. |
| Structured vs. Unstructured | Structured data have predefined formats. Unstructured data lack such organization. |
| Analog vs. Digital | Analog data are physical. Digital data are encoded for computers. |
| Machine-readable vs. Human-readable | Machine-readable is for computers. Human-readable is for people. |
| Quantitative vs. Qualitative | Quantitative data are numeric. Qualitative data are descriptive. |
| Primary vs. Secondary | Primary data are newly collected. Secondary data are reused. |
| Raw vs. Processed | Raw data are unaltered. Processed data are refined. |
| Heterogeneous vs. Homogeneous | Heterogeneous data are diverse. Homogeneous data are uniform. |

Classification criteria help to comprehend and structure data, but their relevance depends on the context in which the data are used and the specific requirements of a given application.

On a building level, the consideration of time can lead to another differentiation. For the same object of assessment, different data are required at different points in time to describe it appropriately. This includes looking at the past, actual, and targeted/projected status of a building or its elements. For example, when a building is at its use stage, as-built planning documents can represent the past status, up-to-date building models the present status, and projections the targeted status. This can correspond to timelines for certain data points. Common examples of this approach involve tracking the condition of particular building elements or assessing the energy performance of a building.

### 3.1.3 Building quality characteristics

One important access to describing a building with data is offered by quality approaches (Lützkendorf & Speer, 2005, p. 187). They can help to determine data needs from a top-down approach and to efficiently communicate building qualities. Conventions to describe and assess buildings based on quality characteristics gained increased attention within the last 25 years along with the development of green building assessment systems. The quality characteristics included in such instruments are related to the goals that are pursued with planning, constructing, and using a building by different actors of the real estate industry. The overall question lies in the capability of a building to serve their needs, offer the respective functionality, and lead to the desired effects on the environmental, social, and economic systems (ISO 15392:2019-12, p. 8).

One important aspect to consider when following a quality approach is to specify the object of assessment. Many quality characteristics can be transferred from a building level to higher levels of real estate management, such as the portfolio or corporate level (Buchholz & Lützkendorf, 2022b, p. 12). At the same time, some qualities are also relevant on lower levels, such as the level of rooms, products, or materials. Quality characteristics can be defined for all life cycle stages of a building. From the perspective of sustainability assessments, it is common to compare quality characteristics from the as-planned stage to the as-built stage (ISO 21931-1:2022-06, pp. 48–49).

One challenge in the definition of quality characteristics is to operationalize the goals of sustainable development for specific objects of assessment. Quality approaches try to modularly translate overreaching goals from a global and society-oriented perspective to goals on a building level. A first step is to define quality dimensions. In the real estate industry, the threefold classification of a sustainable development serves as a basis and is often extended by a technical, functional, and location dimension (Gebäudeforum Klimaneutral, 2025b). However, there is no strict differentiation between these dimensions, since they are overlapping. Next, specific building qualities can be accounted to these dimensions. In a third step, indicators are needed that allow for a quantitative or qualitative assessment of a building quality.

There are recognized indicators for certain building qualities, while for others suitable indicators remain vaguer. A reason for this can lie in the difficulty to quantify and thus objectify certain aspects. Different indicators might be needed to express the same building quality for different actor perspectives. For example, landlords assess the economic quality of a building by evaluating the results of a profitability assessment, while tenants value rental space they can afford.

Table 3.3 gives an overview on building quality dimensions and building qualities. It is based on specifications of building qualities and indicators in standards, green building assessment systems, EU frameworks, and industry standards. Most building qualities and indicators can be applied at every life cycle stage of a building. However, different information sources and data might be necessary at different stages. In the context of a sustainability assessment, building qualities can also be interpreted as assessment criteria.

Table 3.3: Building qualities and indicators based on (Buchholz, 2022; DIN SPEC 91475:2024-03; ISO 21931-1:2022-06)

| Quality dimension/characteristic | Building qualities |
|---|---|
| Economic quality | Whole life cost |
| | Life cycle cost |
| | Profitability |
| | Preservation of value / value stability |
| Environmental quality | Energetic quality |
| | Climate friendliness / impact |
| | Environmental impact |
| | Climate resilience |
| | Resource efficiency and sufficiency |
| | Circularity |
| | Space efficiency |
| | (Local) environment friendliness |
| Social and functional quality | Aesthetic value |
| | Thermal comfort |
| | Acoustic comfort |
| | Visual comfort |
| | Indoor air quality |
| | Accessibility |
| | Suitable usable spaces |
| | Impacts on neighbors |
| | Impacts of maintenance on users |
| | Personal safety |
| | Mobility infrastructure |
| Technical quality | Longevity |
| | Durability |
| | Ease of maintenance |
| | Reconstruction capability |
| | Adaptability and flexible use |
| | Quality of structure |
| | Quality of the building concept |
| | Quality of envelope |
| | Quality of building services |
| | Smart readiness |
| | Quality of building products and materials |
| Location quality | Exposition towards natural hazards and climate risks |
| | Proximity to relevant facilities |
| | Quality of plot |

Extensions and alterations are expected for the relevance of building qualities and indicators in the long term based on the influence of megatrends on the built environment. For BISs, the quality approach can play an important role to classify data from the perspective of actors' information demands.

### 3.1.4 Building-related properties and attributes

The demand for building-related data from various perspectives historically led to different approaches to systematize data about a building. Actors of the real estate industry might all create something different, when they are asked to describe a building with data. Architects see a design plan or a digital building model, technicians a smart system, judges a legal object, investors a potential asset, portfolio managers a column in their management system and so on. All of these actors need different building-related data to fulfill their role.

While the quality approach described in the previous section primarily involves aggregated or evaluated data to express specific building qualities, building-related properties and attributes represent unevaluated data elements. In this context, properties and attributes can cover or describe raw data resulting from data creation and collection. The terms "property" and "attribute" are well known in the context of BIM. A property is defined as an information unit dynamically assigned to a specific entity instance, while an attribute is an inherent information unit within an entity, defined by a specific type or reference to another entity (DIN EN ISO 16739-1:2021-11, pp. 10–13). In natural language, it is often difficult to distinguish between properties and attributes.

Figure 3.2 presents a simplified example of how properties can be used to describe a heating system within a model. It focuses on a radiator and its associated thermal and geometric properties, illustrating how specific properties, such as water input temperature and performance class, can be structured and constrained in a given context.

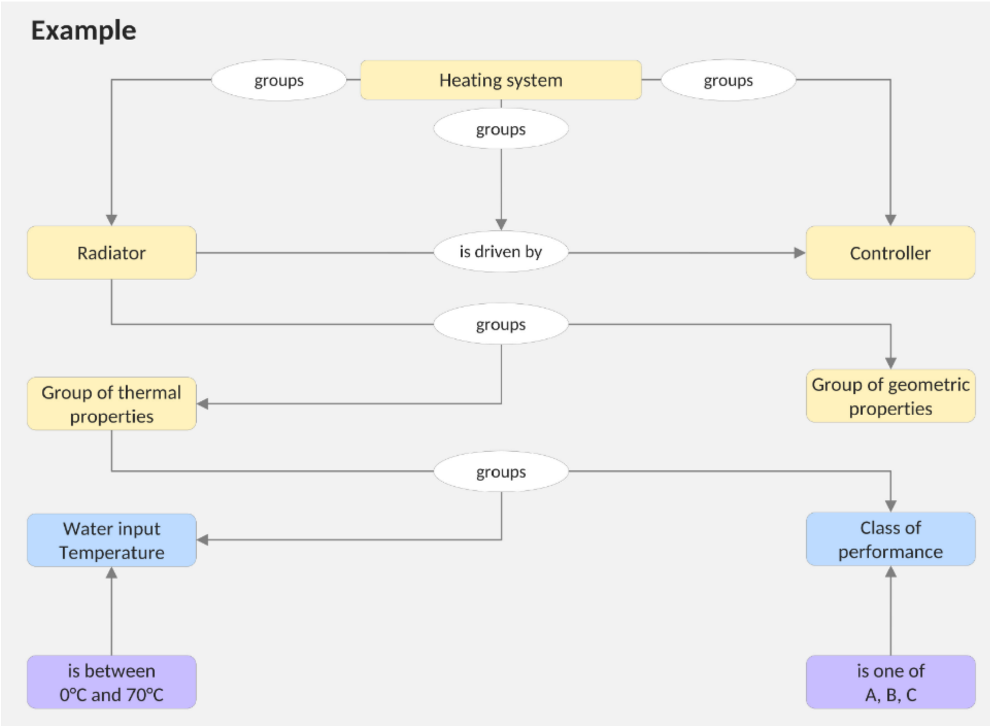



Figure 3.2: Example for a model description of a heating system with building properties and attributes (DIN EN 17549-2:2023-09, p. 14)

## 3.2 Data creation and collection

In this section, methods and frameworks for data creation and collection throughout the building life cycle are identified. These processes are essential for meeting data needs and information management requirements. Furthermore, they are closely linked to data processing and storage, reinforcing their importance in analyzing requirements for BISs. Specifically, this section covers:

- An overview on data creation methods (section 3.2.1)
- Basics on data collection (section 3.2.2) and data collection methods (section 3.2.3)
- An analysis of regulatory systems for data creation and collection (section 3.2.4)

Thus, a comprehensive overview is provided on data creation and collection introducing concepts and information sources which will be referred to at several points throughout the thesis.

### 3.2.1 Data creation and volume in the building life cycle

Data creation is a continuous process throughout the building life cycle, encompassing various types of data that emerge from planning, construction, operation, and eventual deconstruction. While the literature does not provide a comprehensive conceptualization of data creation methods, a general distinction can be made between original data creation, where data are generated without prior empirical input (e.g., during early design), and secondary data creation, where existing data serves as a basis for further derivation (e.g., simulations, projections, or updates based on operational data).

The nature and extent of data creation vary significantly between life cycle stages. Particularly high volumes of data are generated when structural interventions or significant changes occur, such as during the initial planning and construction stages or during major renovations. In contrast, the use stage is typically characterized by a steadier, more incremental data flow (Figure 3.3).

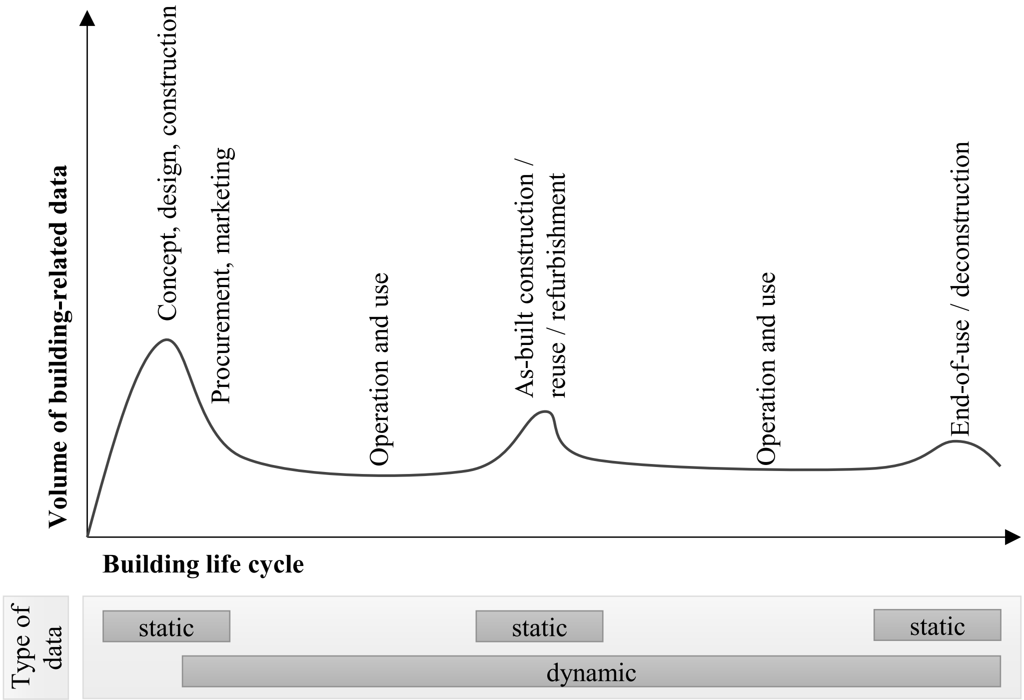



Figure 3.3: Data volume throughout the building life cycle based on Rohde et al. (2011, p. 83)

The actual volume and availability of building-related data, however, depend heavily on how data are managed by different actors across time. Information may be lost, siloed, or never digitized, making data availability a key concern in assessing data quality. These challenges will be discussed further in section 3.4.

## 3.2.2 Basics of data collection

### 3.2.2.1 Types of data collection

“Data collection” refers to processes in which actors gather information in the form of data in respect to their information demand. It can be subdivided into two different types, original and secondary data collection. In comparison to the difference between original and secondary data creation, this distinction is even more established. *Original data collection* refers to the collection of data directly from the object of observation, which can be a building, its components or surroundings for example. *Secondary data collection* addresses data that have already been collected by a different person and that is now available and accessible via a specific information source. Both types can include the collection of alphanumeric as well as geometric data (Mehlis, 2005, p. 57).

The distinction between data creation and data collection can sometimes be blurred, as certain processes inherently involve elements of both. For instance, original data collection, such as surveying or sensor-based monitoring, often results in the generation of new datasets, which can also be viewed as a form of data creation. To address this overlap, the primary intent of the activity, whether to acquire existing information or to produce new data, can be used as a guiding criterion for classification.

#### 3.2.2.2 Data collection in the building life cycle

The purpose of data collection lies in the functions of data to serve actors for decision-making and for them to stay informed generally. Therefore, the processes linked to data collection are often a result from occurring information demands in the life cycle of buildings. Hence, data collection plays a significant role throughout the complete life cycle. Oftentimes, it has already found its way into main tasks in a life cycle stage or in a management activity. An overview on data collection processes and their timing at various stages within the building life cycle can be found in the literature (Figure 3.4).

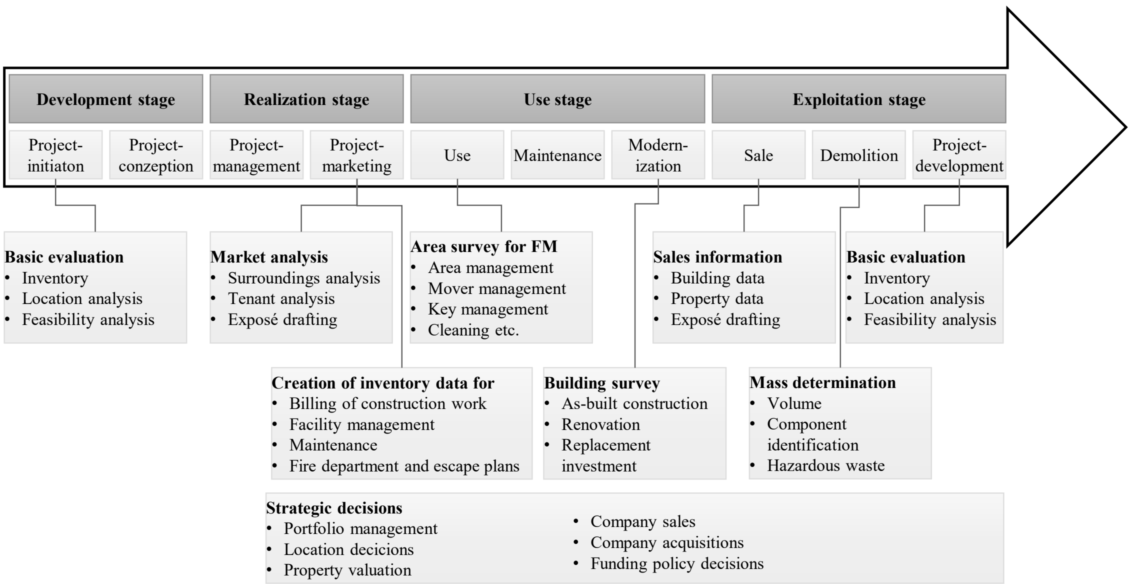



Figure 3.4: Data collection in the building life cycle (Mehlis, 2005, p. 55)

Despite the development of latest trends the overview from Mehlis (2005, p. 55) is still current. While sustainability-related occasions grew in significance, for example, it is not almost impossible to cover all potential situations of data collection.

#### 3.2.2.3 Information sources for data collection

Information sources for building-related data can be classified by dividing them into original and secondary sources. Primary sources refer to original data collection directly on the object of observation. Secondary information sources include building-related data which have already been collected, eventually altered, and then stored in a specific data container. Due to the complexity of real estate, there is a large variety of secondary information sources. In practice, this variety represents one main challenge for building-related information management, since data are distributed across different sources, owned by different actors in various forms. Table 3.4 lists relevant secondary information sources during the life cycle of a building.

Table 3.4: Categories of secondary information sources for building-related data based on (Bundesamt für Bauwesen und Raumordnung [BBR], 2008, p. 26; Talamo & Bonanomi, 2015, pp. 53–57)

| Category | Examples | Purpose |
|---|---|---|
| Design and architectural documentation | Architectural plans, blueprints, BIM models, renderings | Provides foundational data on the building's design, layout, spatial arrangements, and aesthetic intent, critical for understanding the building's structure and purpose |
| Construction and quality assurance records | Construction logs, measurement protocols, quality assurance documents, risk and safety assessments, as-built drawings | Documents the construction process, materials used, safety protocols, and quality checks, ensuring the building is constructed according to plan and safety standards |
| Operational and maintenance documentation | Equipment manuals, maintenance instructions, service catalogues, maintenance logs | Guides ongoing operations and maintenance, providing instructions for upkeep and servicing of building systems and components to extend their lifecycle |
| Legal and compliance documents | Contracts, permits, licenses, regulatory certificates, warranties | Ensures legal and regulatory compliance, documenting agreements, certifications, and permissions necessary for building use and operation |
| Performance and environmental data | Energy and water consumption records, environmental impact assessments, sustainability certifications, utility bills | Tracks building performance metrics related to environmental impact, efficiency, and sustainability, supporting operational improvements and regulatory compliance |
| Geospatial and contextual information | GIS data, site maps, contextual analysis reports | Provides spatial data about the building's location, topography, zoning, and surrounding infrastructure, essential for situating the building within its geographic context |
| Financial and administrative records | Property valuations, insurance policies, leasing and occupancy records, budgeting documents | Manages financial and administrative aspects, including property valuation, insurance coverage, leasing details, and operational budgeting |

The above list is not comprehensive, but rather serves as a brief overview on potential categories and examples of information sources. The emphasis lies on typical information categories rather than formats and systems. In section 3.3, several information sources will be analyzed in more detail to receive insights about the data needs for tasks in the building life cycle.

### 3.2.3 Data collection methods

The following section explains some of the most important methods for collection of building-related data. The focus lies on methods for original data collection directly on a building which are an essential enabler for effective information management and in the context of BIS use.

#### 3.2.3.1 Building survey

A building survey is sometimes interpreted as a reverse design process (Petzold, 2001, p. 16). The primary objective is to gather detailed geometric data that capture the structural dimensions, spatial relationships, and architectural intricacies of a building (Donath, 2008, p. 2). Since especially for old buildings plans and building documentations are rarely available, a majority of research on building surveying has been conducted for the case of historic buildings (Busen et al., 2017, p. 5). However, a building survey can also be carried out if design documents are available but up-to-date data or additional information are required. The scope of a building survey can include both alphanumeric and geometric data (Donath, 2008, p. 4).

There are different levels of detail in building surveys. The basic level incorporates the analysis of the primary structure of a building through architectural drawing and modeling. Among other things, the basic condition of a building becomes clear, comparisons to original designs can be made in case the relevant data are available, while the building gets 'portrayed'. The second level includes more detailed research on the building fabric. Samples are examined in laboratories to receive information about the building materials and the condition of structures and components. The third level is the most detailed type of a building survey and is called "engineer's survey". At this stage, hidden structures, possible damages and defects are identified to receive an even more comprehensive picture of the condition and quality of a building (Mehlis, 2005, pp. 46–47).

#### 3.2.3.2 Holistic building inventory

As the term indicates, a holistic inventory defines the goal of acquiring all building-related data for a single building. The actual process for this differs depending on the life cycle stage, the type of building and the condition of a building. According to Mehlis (2005, p. 48), a holistic building inventory includes the following data categories:

- General data: consist of data that refer to the property and data that refer to the building, e.g. location, address, size, or use type (Mehlis, 2005, p. 67)
- Economic data: concentrate on costs and revenues that result from the operation and use of a building (Mehlis, 2005, p. 81)
- Tax data: address the different types of taxes that take influence on the profitability like income tax, substance tax, or transfer tax (Mehlis, 2005, p. 83)
- Legal data: involve the collection of all legal aspects from public and private law that affect the building and the respective actors (Mehlis, 2005, pp. 82–83)

- Technical data: essentially refer to the processes of a building survey (section 3.2.3.1) or a technical due diligence (section 3.2.3.3) and include the collection of data about the building spaces and the condition of the structure of a building (Mehlis, 2005, pp. 68–79)
- Organizational data: refer to data about the actors and processes of real estate management like portfolio management or facility management (Mehlis, 2005, p. 84)

Considering the types of building-related data, as they have been identified in section 3.1.2, a holistic building inventory tries to cover almost all of these categories. It only lacks the collection of dynamic data, since a building inventory displays the condition of a building at a certain point in time.

#### 3.2.3.3 Due Diligence

The concept of due diligence originates in U.S. capital and investor protection law, referring to a pre-transaction investigation process. Initially established for company takeovers, due diligence applies broadly to business transactions, particularly large investments. Defined as a "detailed examination, analysis, and assessment of the circumstances of the transaction object in fact and in law" (Just & Stapenhorst, 2018, p. 6), it addresses the information gap between seller and buyer to assess risks and opportunities. Due diligence can take different forms depending on perspective, typically distinguishing between seller and buyer due diligence.

In building transactions, due diligence involves a systematic analysis of spatial and market-related factors to inform decision-making (Feldmann et al., 2016, p. 365). It may be part of project development or used in transactions and renovations. The process consists of data collection and evaluation using analytical methods, often categorized into four main types (Tagg, 2018, p. 2):

- *Technical due diligence* assesses the function and usability of a building by analyzing its physical condition, past, and future performance (Feldmann et al., 2016, p. 409; Tagg, 2018, p. 4). It parallels building surveys (section 3.2.3.1) and is also termed a commercial building survey (Tagg, 2018, p. 1). It includes formal data collection, physical assessment, and technical management evaluation, examining aspects like organizational structure, processes, subcontractors, and maintenance documentation. Its findings significantly impact commercial due diligence (Feldmann et al., 2016, pp. 410–411), supporting modernization planning, maintenance cost forecasting, and risk assessment (Royal Institution of Chartered Surveyors [RICS], 2020, p. 4).
- *Commercial due diligence* evaluates a building's economic viability, focusing on value-influencing factors, financial data, and market conditions. It is particularly relevant for rented properties, incorporating location analysis, rental income projections, and operational cost assessments (Schulte, Bone-Winkel, & Schäfers, 2016, p. 407; Tagg, 2018, p. 2).
- *Environmental due diligence* traditionally investigates contaminated sites but increasingly considers climate-related risks, sustainability requirements, and resource scarcity (RICS, 2018, p. 30).
- *Legal due diligence* examines all legal aspects, including rights of disposal, land registry entries, ownership restrictions, building permits, and contractual obligations (Feldmann et al., 2016, p. 408). It identifies legal factors influencing transaction risks and opportunities.

#### 3.2.3.4 Real-time monitoring of buildings

Real-time monitoring is a method for collecting dynamic building-related data that enable continuous observation of energy and water consumption, environmental conditions (such as temperature, humidity, and air quality), occupancy patterns, and structural health aspects. It serves as an overarching term in a broader sense, whereas technical monitoring refers more specifically to a structured task area that has evolved to ensure building performance in times of increased technization in buildings (VDI 6041:2017-07, p. 2). Technical monitoring, also referred to as in-use monitoring when applied in the use stage (Guerra-Santin & Tweed, 2015, p. 189), is closely connected to building commissioning (Figure 3.5), building management, and overall quality management. The primary objective of real-time monitoring is to equip building operators and stakeholders with timely, actionable insights into the building's operational status.

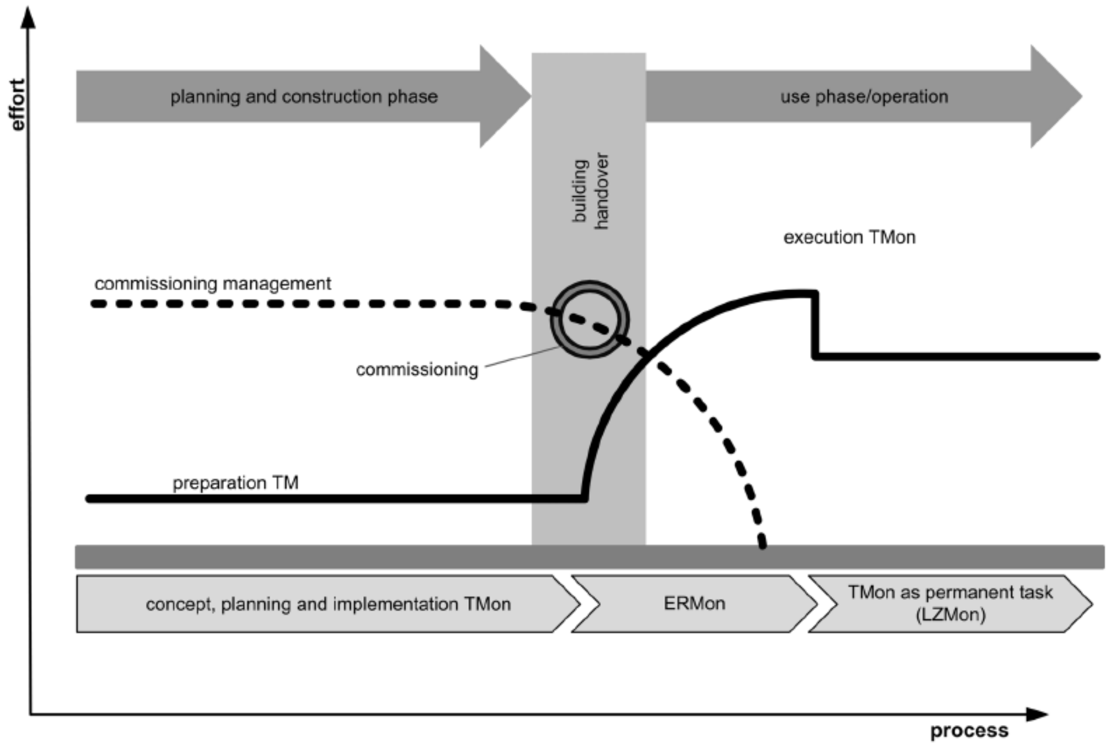



Figure 3.5: Effort for commissioning and technical monitoring throughout the life cycle (VDI 6041:2017-07, p. 39)

In this process, sensors and meters installed throughout the building collect data on resource use and environmental parameters. These data are then aggregated and analyzed, often through building automation and management systems (BAMS). These systems manage data flows and control connected devices to support real-time adjustments for improved performance. By enabling immediate detection of anomalies, inefficiencies, or deviations from target values, real-time monitoring contributes to operational optimization, preventive maintenance, and the long-term assurance of building performance (Hajdukiewicz et al., 2015, p. 1; VDI 6041:2017-07, p. 3).

### 3.2.4 Regulatory systems for data creation and collection

Several regulatory frameworks influence the collection of building-related data. The following selection of legal requirements and frameworks related to collection of building-related data reflects the situation in Germany. In addition to the identification of key concepts, brief evaluations regarding their contribution to information management and BISs will be given where appropriate.

#### 3.2.4.1 Legal requirements

The German Honorarium Regulation for Architects and Engineers (HOAI) provides a structured approach to defining services in construction projects, distinguishing between basic and special services (Table B.2). While nearly all project phases involve documentation, HOAI lacks explicit data quality requirements and clear instructions on data scope. As a result, much of the collected data remain siloed with individual actors and are rarely transferred across life cycle stages. Despite these limitations, the systematic structure, legal foundation, and popularity of HOAI provide a strong foundation for standardizing building-related data collection at early life cycle stages, particularly in later project phases.

The German Construction Contract Procedures (VOB), particularly Part C, set contractual and technical requirements for public construction projects. VOB C, structured around DIN standards (DIN 18299:2023-09, pp. 2–5), defines data collection requirements for specific tasks, such as material properties and compliance checks. However, the fragmentation of standards across multiple specifications results in disjointed documentation, making it difficult to achieve a comprehensive and integrated dataset for an entire project. This structural limitation reduces VOB's effectiveness in facilitating interoperable and reusable building-related data.

The "Baufachliche Richtlinien Gebäudebestandsdokumentation" (BFR GBestand) establish documentation standards for public buildings to enhance real estate management and operational efficiency (Bundesministerium des Innern, für Bau und Heimat [BMI] & Bundesministerium der Verteidigung [BMVg], 2021, p. 1). The guidelines categorize building-related data into alphanumeric and geometric datasets, distinguishing between basic and extended documentation requirements (BMI & BMVg, 2021, p. 6). Despite their structured approach, their applicability remains largely confined to public institutions, limiting broader industry adoption. However, the promotion of BIM and standardized data maintenance processes under BRG offers a potential model for improving data quality in broader regulatory contexts.

The BFR GBestand is part of the regulatory framework for federal construction projects in Germany (RBBau). Another relevant guideline within this framework that defines data requirements is the "Baufachliche Richtlinien Recycling" (Construction Guidelines for Recycling) (BMI & BMVg, 2018). These guidelines serve as a valuable reference not only for state institutions but also for industry practitioners, particularly in determining building element and material data needs at the end-of-life stage.

#### 3.2.4.2 Standards

Several standards specify requirements for the creation and collection of building-related data. They help establish a shared understanding by defining terminology, structuring documentation, and outlining methodological approaches. While their adoption depends on voluntary agreements between actors, some regulations also reference specific standards, increasing their relevance in practice. In Germany, standardization efforts are primarily shaped by the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), and the German Institute for Standardization (DIN). Table 3.5 provides an overview of selected standards that indicate data and documentation needs across different phases of the building life cycle.

Table 3.5: Selection of standards for data collection and creation throughout the building life cycle

| Standard | Focus | Key Specifications |
|---|---|---|
| DIN 32835-1:2007-01 | Technical documentation for facility management | Defines terms, methods, and hierarchy of documentation; distinguishes between construction and use-stage documentation |
| DIN Fachbericht 151:2007-01 | Construction documentation for facility management | Lists documents required for construction; classifies them into basic and special documents; references regulatory frameworks (e.g., HOAI, VOB) |
| DIN 32835-2:2007-01 | Use-stage documentation for facility management | Proposes structured documentation of building parts, components, and rooms; emphasizes transfer of construction data to use-stage records |
| VDI 6026:2015-04 part 1.1 | Documentation of building services | Aligns with planning stages (HOAI) and service processes (DIN 276); specifies required documentation for different project phases |
| DIN SPEC 91462:2022-02 | Property management services | Defines service requirements for property management companies, specifying commercial, technical, legal, and economic responsibilities. Provides insights into data needs for property management |
| VDI 6070 Part 1 | Room books for life cycle documentation | Defines structuring principles for alphanumeric data; attributes evolve throughout the building's life cycle |
| VDI-MT 3810 Part 1:2023-03 | Documentation for building operation and maintenance | Specifies requirements for maintaining operational and maintenance data, integrating diverse data points |
| VDI 6039:2011-06 | Building commissioning documentation | Ensures functionality of building services through systematic testing, verification, and structured documentation |
| VDI 6210:2024-10 part 1 | Demolition documentation | Defines processes for planning, execution, and post-demolition activities, including material handling and waste management |

The listed standards specify data and documentation requirements across different aspects of the building life cycle. While some focus on technical documentation and facility management, others address property management, building services, and operational processes. A shared emphasis lies in structured classification, data consistency, and accessibility, yet their scopes and methodologies differ.

DIN 32835-1, DIN Report 151, and DIN 32835-2 define documentation principles for facility management, distinguishing between construction-phase documentation and operational records. While DIN Report 151 focuses on required documents during construction (Table B.3), DIN 32835-2 addresses use-phase documentation, emphasizing data transfer and updates (Table B.4).

VDI 6026 specifies building services documentation, aligning with HOAI and DIN 276 to structure documentation across planning and execution stages. It highlights revision documentation at project completion, ensuring technical records support long-term building operation.

DIN SPEC 91462, unlike the construction-focused standards, defines service requirements for property management. It standardizes commercial, technical, legal, and economic responsibilities, providing insights into building-related data needs throughout the use stage.

VDI 6070-1 and VDI 3810-1 focus on operational documentation. VDI 6070-1 structures room books, progressively detailing spaces, components, and technical installations. Room books are highlighted as a central instrument for building documentation in DIN 32835-2 too. A room book is supposed to function in a job-sharing approach along with building, facility, furnishing, and equipment books (Figure B.1). VDI 3810-1 defines building operation and maintenance documentation, integrating data for facility management, compliance, and performance tracking. It takes in a similar role as DIN 32835-2, but considers more recent developments in the industry.

VDI 6039 and VDI 6210 address transition and end-of-life phases. VDI 6039 ensures building commissioning through structured verification and documentation, supporting a seamless transfer from construction to operation. VDI 6210 provides guidance on demolition documentation, including material handling, waste management, and environmental considerations.

Despite their differences, these standards collectively can provide a good basis for structured documentation practices to improve data organization, decision-making, and long-term information management. One reason for their limited practical relevance lies in the fragmentation of conventions. Therefore, the specifications made within the standards will be integrated into the analysis of building-related data needs in the following section.

## 3.3 Building-related data needs

This section analyzes the need for building-related data to define requirements for the data content of a BIS. The objective is to identify the data created and needed for different tasks while assessing their relevance throughout the life cycle. Beyond analyzing actors' information demands, as explored in previous research, such as in Starzner et al. (2007) or Rohde et al. (2011), this study aims to gain a deeper understanding of the objective data needs required for decision-making and task execution in the building life cycle. This approach is regarded as more meaningful in times, where actors fulfill roles and tasks increasingly dynamically. Compared to similar approaches as the one from Mehlis (2005), the analysis provides an up-to-date perspective and a more systematic and integrated result.

First, the broader decision context in the real estate industry is analyzed to connect actor- and task-based data needs (section 3.3.1). To complement this view, occasions in which actors require information are identified (section 3.3.2) before progressively analyzing building-related data needs across different situations and task areas (sections 3.3.7 to 3.3.7). The findings are synthesized into a hierarchical structure (taxonomy) for building-related data (section 3.3.8).

The analysis builds on prior literature regarding the information needs of specific actors and tasks, and incorporates recent industry developments to provide context within the industry's shifting landscape shaped by ongoing trends and megatrends.

### 3.3.1 Decision context of actors

Decisions of actors in the real estate industry are a complex undertaking, yet the topic does not get much attention in the literature (Krieger & Lausberg, 2021, p. 2). The context in which actors make their decisions is of special interest since the supply with data and information can significantly contribute to their decision behavior. Additional to other functions (section 2.2.1.2), information primarily supports decision-making. However, the decision-making process and its consequences are influenced by many parameters and thus make it difficult for actors to approximate their objective information needs (section 2.2.1.3).

According to decision theory, a decision process can be modeled so that it consists of four main components: a decision rule, action alternatives, results and states of the environment (Laux et al., 2014, p. 30). In the real estate industry, these components can take in various forms. Actors pursue different goals on different occasions for different objects of observation. Goals depend on the main perspective on real estate and on external factors. Occasions either occur from internal or external factors. The object of consideration can be represented by a building, components of a building, a whole building stock or an entire organization, for example. This means that the *decision rule* can be highly individual, whereas the respective object of observation sets the frame for possible *action alternatives*. Actors can also be influenced through other actors in their decisions, and they might form special actor constellations. The *result* of a decision does not necessarily include direct actions, but often leads to further decision. *States of the environment* are multi-dimensional and include the immediate local environment of an actor as well as larger economic, environmental, societal, or political developments (Figure 3.6).

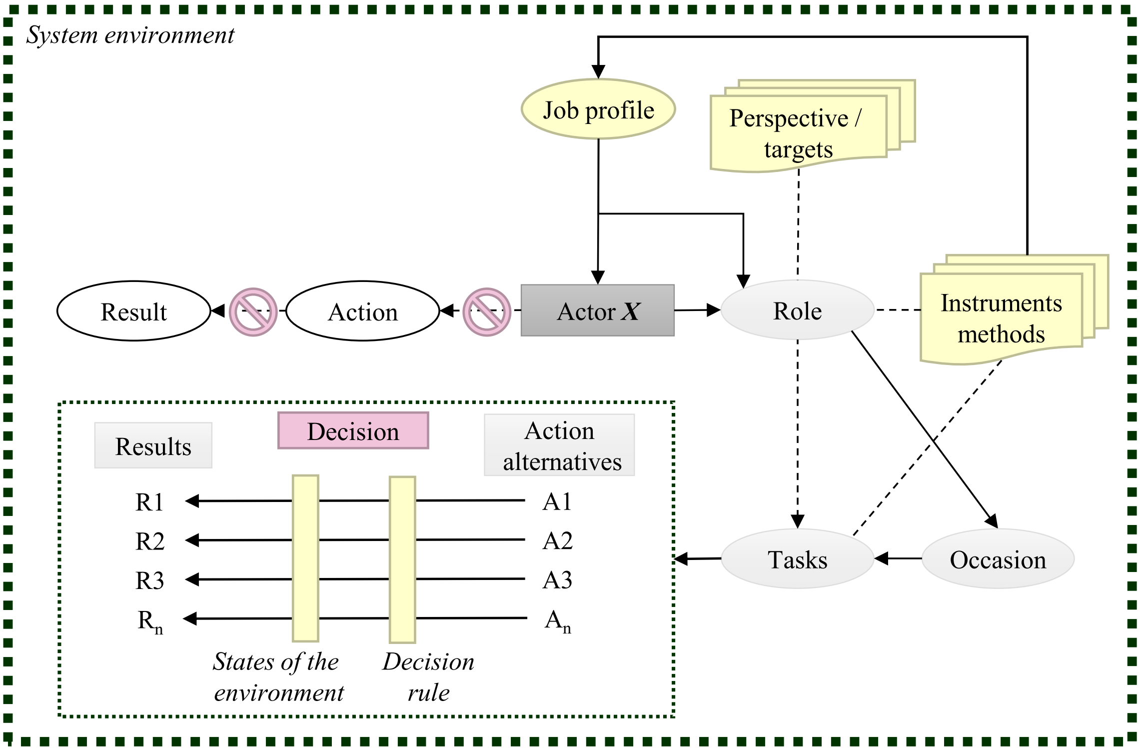



Figure 3.6: Decision context of actors in the context of their roles and tasks based on Bundesministerium für Verkehr, Bau und Stadtentwicklung and BBR (2008, p. 23)

Figure 3.6 illustrates that making decisions that lead to actions is not a straightforward process for actors. In practice, different actors usually face different tasks and eventually share different perspectives on their objects of observations. For the real estate industry, these perspectives can be examined on the basis of actors' legal status: Private actors are usually represented by private home-owners in their role as owner-occupiers or landlords. Institutional actors are any kind of building owners or building-related service companies that have a legal status as a company. Public actors are represented by public authorities on state or county level (Enseling et al., 2023, p. 115). In order to better understand influential factors for decision-making several criteria are applied to compare private, institutional, and public actors (Table 3.6).

Table 3.6: Influential factors on the decision context for different actor perspectives on real estate

| | Private | Institutional | Public |
|---|---|---|---|
| Object of observation | Single buildings and building components… | Building stock, single buildings and building components, organizational aspects… | Building stock, single buildings and building components, organizational aspects |
| Main goals/motives | Economic viability, comfort, self-actualization | Profitability | Population welfare, climate and environmental protection, satisfaction of societal needs |
| Influence of boundary conditions | High | Very high | Very high |
| Expertise | Low | Medium to high | Medium to high |
| Resources | Little | Many | Many |

Many critical decisions must be made throughout a building's life cycle, from project initiation, realization, and financing in the early stages to use, maintenance, and modernization during operation, and ultimately to deconstruction. To apply decision rules and assess states of the environment, as illustrated in Figure 3.6, actors rely on building-related data as an essential basis. Table B.5 presents a selection of key decisions along with the typical decision basis required to support them.

## 3.3.2 Occasions of information demand

An occasion of information demand can be understood as a point or a certain timespan in the building life cycle in which actors perceive a subjective need for information. Occasions can also be perceived as triggers, since they often lead to specific tasks that follow. These types of triggers (section 3.3.2.1) provide a basis for analyzing the objective data needs in different tasks. Additionally, occasions result from the interest of actors (section 3.3.2.2). This distinction is not strict, and the types are not mutually exclusive.

### 3.3.2.1 Task-related occasions

The special feature of task-related occasions of information demand is that they usually trigger a set of building-related tasks. The fulfilling of these tasks represents a necessary prerequisite in most cases to develop, construct, operate, and use a building properly. Along with the tasks, the information demand that occurs at an occasion is specified. Actors perceive occasions throughout the building life cycle along with their role that is influenced by their motives, incentives, and needs (Buchholz & Lützkendorf, 2024, p. 3).

Table 3.7 contains occasions and the tasks that are usually triggered by that. These tasks are based on the tasks that were identified for different perspectives on real estate (section 2.1.4). One important aspect in task-related occasions is that both the occasion and the tasks that follow are directly related to a building.

Table 3.7: Occasions of information demand in the building life cycle

| Occasion | Tasks |
|---|---|
| Need for new construction | Project development, building design, construction management, financing, marketing |
| Real estate transactions | Marketing, building analysis, valuation, financing |
| Change of building user / tenant | Marketing, building analysis |
| Change in building function or occupancy type | Building analysis |
| Wear and tear, failure of building elements | Maintenance, repair, replacement, refurbishment |
| Need for as-built construction / refurbishment | Building analysis, feasibility analysis, building design, construction management |
| Need for deconstruction, demolishment | Construction management |

Table 3.7 contains an overriding view on occasions and tasks. In practice, tasks are intertwined and need to be broken down into subtasks according to the specific context.

In addition to occasions on the building level, there are also occasions on the corporate level, for example as a result from non-financial reporting obligations.

#### 3.3.2.2 Interest-based occasions

There are additional occasions of information demand in the building life cycle that do not necessarily trigger certain tasks, but rather derive from the interest of actors. This does not imply that actors do not use the information for their purposes. However, the tasks included are less obligatory, and the occasions on which they occur are more random. Examples include the necessity or desire…

- to assess the sustainable performance of building.
- to assess building performance in relation to investment strategy and portfolio strategy.
- to optimize building use, for example in terms of running costs, energy consumption or the operation of building services.
- for interior design from the perspective of intended use, such as determining the location of electrical wiring or the dimensions of rooms.
- to ascertain the condition of building components and materials for the purpose maintenance management.
- to assess the performance of building structures, components, and materials by construction product manufacturers or contractors, for example.
- to collect data on the national building stock by the public sector.

The occasion itself is not always essential for actors to articulate their information demand, but specifying it can provide valuable context.

The plentitude of potential occasions of information demand becomes apparent when considering the use-oriented perspective specified by CREM. Table B.6 lists several examples for such occasions for different building use types.

#### 3.3.2.3 Selection of contexts for the analysis of data needs

Task-based and interest-based occasions are collectively referred to as contexts in which building-related data are needed, both of which are considered in the analysis following. The selection of contexts is based on their relevance for building-related information management and includes:

- Tasks within life cycle stages: development and construction, use, end-of-life
- Cross-functional tasks: property valuation, risk management, marketing
- Public sector tasks
- Sustainability assessment
- Non-financial reporting

The aim of this selection is to cover building-related data needs as broadly as possible while maintaining a structured and manageable scope. It integrates both established contexts (e.g., life cycle tasks) and emerging trends in the real estate industry (e.g., non-financial reporting). Further details on the relevance of each context, the specific tasks considered, and the analyzed information sources are provided in the respective sections.

Many actors in the real estate industry engage in these contexts. Table B.7 provides an overview of the typical actors involved and their level of engagement, helping to contextualize the findings of the following analysis.

### 3.3.3 Building-related data needs throughout the life cycle

#### 3.3.3.1 Data needs at the development and construction stage

The early life cycle stages generate a vast amount of building-related data, primarily to support decision-making and satisfy the information needs of key actors such as planners, construction firms, and project managers. The development and construction stage are particularly crucial as they establish the foundational data required for managing a building throughout its life cycle. This is reflected in the variety of information sources analyzed, which indicate that data needs extend beyond immediate tasks to also serve future life cycle stages.

A key category in this stage is master data, which provides fundamental contextual information about the building and construction project. This includes data on intended usage, involved actors, and location, as well as planning and construction processes. The HOAI, for instance, specifies documentation requirements covering needs assessments, location analyses, feasibility studies, and cost calculations (HOAI, 2013), while similar aspects are addressed in VDI 6026:2015-04 part 1.1.

Inventory data play a major role in capturing the physical realization of a building. While early design documents primarily support planning, inventory data ensures that as-built conditions are documented. Multiple information sources emphasize the necessity of recording structural components and building services, including testing protocols and maintenance instructions. Additionally, building geometry and area data are relevant, particularly in connection with virtual building models and floor plans. VDI 6070 Part 1 highlights the importance of documentation related to room, facilities, equipment, and furnishing books (Figure B.1).

Economic and legal data primarily cover construction costs, contractual agreements (including rental, maintenance, and service agreements), and essential approvals such as building permits. These data points provide the regulatory and financial framework necessary for both project execution and future operational stages.

Building performance data play a comparatively minor role at this stage, as performance metrics become more relevant during building operation. The analyzed sources indicate that instruments such as technical monitoring standards and green building certification systems primarily address performance in later life cycle stages, which are covered in subsequent sections.

A structured overview of the data needs identified for this life cycle stage is provided in Table B.8.

#### 3.3.3.2 Data needs at the use stage

The use stage is characterized by extensive building-related data needs due to its significantly longer duration compared to other life cycle stages and the multitude of decisions, tasks, and actors involved. This stage reveals distinct perspectives on real estate, performance-, return-, and use-oriented, each generating diverse data requirements in contexts such as renovations, maintenance, portfolio management, and tenant administration. Several information sources were analyzed to account for these different perspectives (Table B.9).

A fundamental role is played by master data, which serve as a foundation for nearly all tasks. These include essential information such as building usage type, ownership details, location data, and key dates from planning and construction records. Additionally, contextual data on building operation and usage patterns are crucial for managing the building efficiently.

Regarding inventory data, up-to-date information on building geometry, components, and services is essential. These data support both strategic real estate management decisions and the technical-physical aspects of facility management. While construction documentation, as defined in DIN Fachbericht 151:2007-01 or VDI 6026:2015-04 part 1.1, provides a basis, it is often insufficient for the specific requirements that emerge during the use stage. Therefore, a transformation into use documentation, as outlined in DIN 32835-2:2007-01, is necessary. A distinctive situation exists in the case of major renovations, so that in terms of scope and complexity alone, this can again be referred to as construction documentation

A key technique for collecting real-time building data is technical monitoring, which encompasses the recording, storage, visualization, and analysis of operational and process variables (section 3.2.3.4). Table 3.8 outlines key data categories collected through technical monitoring, including operating parameters, energy consumption, system states, and environmental conditions.

Table 3.8: Examples for data points collected through technical monitoring based on (Guerra-Santin & Tweed, 2015, p. 192) and Arbeitskreis Maschinen- und Elektrotechnik staatlicher und kommunaler Verwaltungen (2020, p. 21)

| Category | Examples of Data |
|---|---|
| Operating parameters | Temperatures (supply/return, room, outdoor), pressures, flow rates, humidity, energy performance. |
| Energy and Consumption | Electricity usage, heating/cooling energy, gas, water consumption. |
| Control and Regulation | Operating times, on/off states, setpoint/actual deviations. |
| Condition and Maintenance | Error messages, maintenance schedules, sensor/actuator states. |
| Weather and Environment | Outdoor temperature, weather conditions, sunlight hours, wind speed. |
| Indoor climate | Air quality ($CO_2$ levels, pollutants), lighting intensity (lux). |
| System-specific data | PV production, battery status, elevator movement/load data. |

For return-oriented tasks, such as portfolio, asset, and property management, data needs are less standardized. Variations arise due to differing owner requirements, building types, and data collection methods. Additionally, the level of aggregation increases from property to asset and portfolio management. Compared to the performance perspective, the return-oriented perspective relies more on economic, legal, and performance data, including financial records, contracts (e.g., with tenants or service providers), regulatory documents (e.g., EPCs), and user satisfaction metrics. Ensuring reliable data quality and format is critical, particularly at higher aggregation levels such as portfolio or investment management. While sustainability-related data are increasingly relevant in real estate management, they are primarily addressed in the sections on sustainability assessment (3.3.6) and non-financial reporting (3.3.7).

The use-oriented perspective overlaps with other perspectives but places greater emphasis on aspects such as furnishing, equipment, and fixtures. In CREM, data needs arise from leveraging buildings as corporate resources or considering them as influencing factors in business processes.

Finally, private users, including owner-occupiers and tenants, exhibit data needs that are also reflected in Table B.9. However, their requirements are often highly specific and dependent on individual motives. Compared to professional building owners, their data needs tend to be at a much higher level of detail.

#### 3.3.3.3 Data needs at the end-of-life stage

The end-of-life stage, as defined in section 2.1.3, encompasses the deconstruction or demolition of a building. The decision to deconstruct or demolish is typically made when a building reaches the end of its economic or technical lifespan, either because continued operation is no longer profitable or its structural condition has deteriorated beyond feasible modernization. Although this decision is technically made during the use stage, it is categorized here due to its direct relevance to end-of-life processes.

Much of the data required at this stage align with those from earlier life cycle stages, particularly information on building components, services, and geometry. However, for actors involved in deconstruction planning and execution, it is crucial that these data remain up-to-date to support informed decision-making.

A critical factor is the identification of hazardous materials, essential for worker safety and legally compliant waste treatment. Additionally, the structural health of the building must be assessed to determine deconstruction feasibility (BMI & BMVg, 2018, pp. 41–44). Ideally, these data are systematically recorded and maintained during the use stage. Otherwise, they must be newly gathered through inspections, audits, or surveys. These processes should be documented within a deconstruction log to ensure process transparency and compliance (VDI 6210:2024-10 part 1, pp. 9–10).

Beyond technical data, the analyzed information sources indicate additional data needs, including building usage history, maintenance records, financial documentation for deconstruction, deconstruction permits, statutory protections, and environmental risk assessments (Table B.10).

## 3.3.4 Data needs in cross-functional tasks

### 3.3.4.1 Property valuation

Property valuation is heavily dependent on building-related data, which form the basis for determining market value, investment potential, and financial risks. The required data typically include master data (e.g., building use type, location, age), inventory data (e.g., construction type, quality, size, heating system, room layout), and legal factors such as property rights, tenancy law ties, statutory protections, and encumbrances.

Beyond these fundamental data categories, external factors, such as legal requirements, valuation methodologies, actor preferences, and emerging market trends, also influence data needs (Meins et al., 2011, p. 6). Table 3.9 provides an overview of common property valuation methods and their specific building-related data needs.

Table 3.9: Overview on methods for property valuation based on (ImmoWertV, 2021), Michl (2018), and International Association of Assessing Officers (2018)

| Method of property valuation | Underlying logic | Special building-related data needs |
|---|---|---|
| Comparable sales method | Determines property value by comparing it to similar buildings | Property characteristics, building characteristics (type, construction method, size, condition) |
| Replacement cost approach | Determines value by summing preliminary replacement costs of the building and land value | Inventory data on building elements |
| Investment method | Calculates value based on potential income generation in the market | Economic data (rental revenues, operational costs) |
| Hedonic pricing method | A specialized comparable sales method that uses statistical regression analysis on sales prices | Similar data as in the comparable sales method but with higher granularity and more quantifiable parameters |
| Automated Valuation Models (AVMs) | Data-driven valuation approach using machine learning and statistical models to analyze large datasets | Extensive building-related and market data, including historical sales prices, rental income, local economic indicators, building condition, and energy efficiency ratings |

A continuing trend in property valuation is the growing integration of sustainability aspects into valuation methods. This shift reflects the increasing importance of environmental and social building qualities in determining property value. Previous research has established fundamental principles and guidelines for incorporating sustainability into valuation practices (Jäger, 2021; Lorenz & Lützkendorf, 2011; Meins et al., 2011; H. Schäfer et al., 2010). Another trend refers to the ongoing automation of property valuation and the integration with BIM models and machine learning algorithms (Su et al., 2021).

Recent market developments indicate a gradual response to these needs, as meta-analyses show a positive impact of sustainability on real estate profitability (Fuerst & Dalton, 2019, p. 174). As a result, data needs for property valuation are evolving, requiring additional building attributes to be considered in valuation models. The guidelines by Meins et al. (2011) (“NUWEL”) significantly enhance the list of relevant data points compared to traditional property valuation, which is reflected in Table B.11.

### 3.3.4.2 Risk management

The literature highlights the importance of comprehensive building documentation for effective risk management (H. Schäfer et al., 2010, p. 57; Worschech, 2024, p. 148). As a cross-functional task, risk management requires a broad range of building-related data. To determine these data needs, various information sources were analyzed, including "VOEB-Immobilienanalyse", a methodology for assessing the opportunity-risk profile of real estate from a banking perspective, alongside insights from Urschel (2010) and industry-specific insurance forms (Table B.12).

The analysis reveals that risk management depends on all types of building-related data, including:

- Master data (e.g., building usage, location, age, maintenance status)
- Inventory data (e.g., building elements, geometry, functional characteristics)
- Economic data (e.g., operating costs, revenues, property development potential)
- Performance data (e.g., energy performance, emissions, environmental impacts)

A key trend in risk management is the growing integration of sustainability aspects into risk assessment practices. Worschech (2024, pp. 124–134) developed a catalog of building characteristics to support this shift, enhancing portfolio and risk management through established industry instruments. Additionally, he identified building characteristics influenced by megatrends shaping future real estate risk management (Worschech, 2024, pp. 139–141). In the context of building-related data, he distinguishes between location characteristics and building characteristics. Many of these characteristics align with building qualities identified in section 3.1.3, further reinforcing the link between sustainability and risk assessment in real estate.

### 3.3.4.3 Marketing

In real estate marketing, building characteristics serve as a key element of product design. Actors involved in marketing rely on a substantial amount of building-related data to fulfill their tasks, particularly in transactions and rentals. Real estate agents specialize in mediating between property owners and potential buyers or tenants, requiring access to essential property documentation. Helfrich (2021, pp. 53–72) lists key documents used as information sources, including:

- Land register extracts (ownership, property size, restrictions, mortgages)
- Parcel maps from land registers
- Elevation drawings, floor plans, living space calculations
- Building descriptions
- Energy performance certificates

A commonly used tool in real estate marketing is the real estate brochure (Exposé), which condenses building-related data to highlight key features and amenities. The focus lies on general information (e.g., location, year of construction, last renovation) and inventory data (e.g., living space area, floor plans, photo documentation, furnishings, and functional building properties such as accessibility and space efficiency) (Table B.13).

New trends and technologies are shaping data needs in real estate marketing. The increasing use of social media, video content, and virtual tours enhances property presentation, requiring more detailed building data. Tools such as virtual reality (VR) applications rely on accurate digital building models, often derived from BIM tools (Azmi et al., 2022, pp. 872–873). These advancements influence which data real estate professionals prioritize to create immersive and engaging marketing materials.

### 3.3.5 Special information needs by the public sector

The public sector is responsible for supervising compliance with laws in the real estate industry. To fulfill this role, public authorities require selected building-related data on properties, buildings, actors, and processes. Given the variety of data needs, the public sector employs multiple instruments to collect and manage building-related information, primarily through three distinct yet interrelated administrative systems:

- Real estate cadasters: Focus on the spatial and physical characteristics of land parcels, documenting boundaries, sizes, land use types, and geographic coordinates. These records provide foundational spatial data essential for urban planning and infrastructure development.
- Land registers: Address the legal dimensions of property, recording ownership, mortgages, and easements to ensure secure property rights and facilitate real estate transactions.
- Building registers: Concerned with the attributes and conditions of buildings, including construction year, usage, energy efficiency, and technical specifications (Krause et al., 2022, pp. 26–27).

These instruments are often closely related and the differences are not always clear. Together, however, they provide essential functions for the real estate industry (Adlington et al., 2021, p. 6).

In Germany, real estate cadasters and land registers are already in place and serve as data sources for various administrative purposes. However, the introduction of a national building register remains a subject of ongoing discussion (Krause et al., 2022, p. 25). Such a register could reduce reliance on costly statistical surveys by maintaining structured, up-to-date building-related data. In contrast, countries like Denmark and Switzerland have already implemented comprehensive building registers, which contain master data (e.g., unique identification numbers, addresses, geographic coordinates, usage type, construction year, maintenance records), inventory data (e.g., building size, layout, heating system, materials, water supply, waste management connections), and legal data (e.g., property rights, statuary protections, building permits) (Table B.14).

In Germany, some of these data are currently collected periodically through statistical surveys such as the Mikrozensus, highlighting the fragmented nature of public-sector building data collection.

### 3.3.6 Data needs in sustainability assessment and management

The importance of sustainability assessment in the real estate industry is increasingly recognized, driven by climate change and environmental crises. Since sustainability principles, spanning economic, environmental, and social perspectives, affect the entire building life cycle, they influence decisions across all stages and for all actors involved.

To integrate sustainability principles into decision-making, a variety of instruments, tools, and methods have emerged in recent years. These sustainability assessment instruments provide a valuable foundation for identifying building-related data needs. Among the most significant are:

- Standards from national and international standard bodies, such as ISO 21931-1, DIN EN 15978 or DIN SPEC 91475 (overview in section B.6.8)
- Building certifications, often referred to as green building certification systems or labels, which assess buildings against predefined sustainability criteria and assign a rating (e.g., “Qualitätssiegel Nachhaltiger Wohnungsbau”, NaWoh)
- Benchmark systems, such as the Global Real Estate Sustainability Benchmark (GRESB), which facilitate industry-wide sustainability comparisons.

Sustainability assessments rely heavily on building-related data across different categories. Master data, such as the building use type and location, are essential to define system boundaries, while inventory, economic, and performance data provide the critical inputs for calculations, analyses, and assessments. A distinct characteristic of sustainability assessments is that they do not merely consume data, they also generate new information. The assessment process itself produces additional performance data, mostly in the form of indicators, contributing to a refined understanding of a building’s sustainability. As such, sustainability assessments serve as both a data consumer and an information source.

### 3.3.7 Information demand through reporting obligations

The demand for building-related data extends to the corporate level of real estate management, particularly due to the rise of sustainability reporting. Also referred to as non-financial reporting, sustainability reporting has evolved into a key tool for communicating a company's sustainable performance to its stakeholders. While the concept itself is not entirely new, established frameworks such as the Global Reporting Initiative (GRI) have been in place for over two decades (Global Reporting Initiative [GRI], 2024), recent policy developments in Europe have significantly reshaped the reporting landscape.

A major driver of change has been the European Commission’s legislative efforts under the European Green Deal, following the Paris Climate Agreement in 2015. Several instruments introduced in this context have increased the demand for building-related data:

- The EU Taxonomy, initiated in 2020, establishes a classification system that defines criteria for determining whether an economic activity qualifies as sustainable or non-sustainable (section B.6.9). Compliance requires inventory data on functional building characteristics, such as resilience against climate risks, primary raw material shares in building materials, or air tightness (Climate Delegated Act, 2021).
- The Sustainable Finance Disclosure Regulation (SFDR) mandates financial market participants to disclose how ESG factors are integrated into investment decisions. While its primary focus is on financial institutions, it indirectly impacts the real estate industry,

as investors demand building-related data from the companies they fund (SFDR, 2019; Draft Delegated Act (RTS), 2022).

- The Corporate Sustainability Reporting Directive (CSRD), adopted in 2022, replaces and expands the Non-Financial Reporting Directive (NFRD). It introduces stricter and broader reporting requirements, significantly increasing the number of companies subject to mandatory sustainability disclosures (CSRD directive, 2022; C/2023/7020 final, 2023). The phased implementation began in 2024, with first reports due for the 2024 fiscal year.

While the EU Taxonomy directly specifies building-related economic activities, the SFDR and CSRD create indirect but substantial reporting demands. Real estate companies must collect and process large amounts of building-related data, particularly regarding building performance. The SFDR establishes requirements for disclosing key indicators, such as energy performance, greenhouse gas (GHG) emissions, and waste volumes. Many of these indicators also play a role in CSRD reporting, though their relevance is subject to a double materiality assessment, which determines which topics outlined by the directive are material to the reporting company.

Most recently, the OMNIBUS Directive introduced a deferral of certain reporting requirements under the CSRD, slightly easing the immediate reporting pressure on some companies (European Commission, 2025). However, this does not diminish the long-term need for substantial amounts of building-related data as mandated by the CSRD.

## 3.3.8 Summary of building-related data needs

### 3.3.8.1 Selected observations in data needs

Despite varying perspectives, one of the key findings from the analysis is that many building-related data points are required multiple times across different contexts. This is particularly true for data that remain largely static over time, such as:

- Master data (e.g., location, primary building usage)
- Inventory data (e.g., building dimensions, construction type)
- Legal data (e.g., building permits, statutory protections)

The relative stability of these data points can have different reasons: Some remain unchanged due to the nature of the built structure, while others retain their validity due to legal constraints (e.g., permits and contractual agreements).

Beyond these static data types, other frequently used data points relate to specific building characteristics that change more frequently, for instance, technical conditions, operational performance, or economic values. These data points are often subject to updates due to maintenance activities, market fluctuations, or regulatory changes. They are needed multiple times throughout the building life cycle too with slightly more specific requirements on their quality. In any case, the possibility of reusing information on different occasions is made clear.

Only a minority of data points are highly specific to individual tasks, meaning that they are rarely required beyond their immediate context. This can refer to specific building element maintenance conditions in facility management or performance metrics in sustainability assessment. However, even these task-specific data points may indirectly contribute to broader information management processes, particularly when aggregated or linked to other datasets.

#### 3.3.8.2 Classification approach

To systematically condense and structure the diverse needs for building-related data, a hierarchical classification approach in the form of a taxonomy has been chosen. This approach offers several advantages:

- Intuitiveness and comprehensibility: Hierarchical structures are easy to navigate and provide a logical way to organize complex data needs.
- Alignment with industry standards: Such classification methods are well established in the real estate industry, making them familiar and applicable in practice.
- Balancing abstraction and detail: The taxonomy enables a high-level overview of data categories while allowing for more granular differentiation where necessary, without requiring exhaustive specification of all individual data points.

For improved clarity and usability, each data category and data point has been assigned an unambiguous identifier. A structured numbering system based on three-digit codes was applied, following conventions successfully used in the real estate industry, such as in DIN 276:2018-12 and DIN 277:2021-08.

At the highest level, the taxonomy divides building-related data into data domains, i.e. higher-level categories, derived from the preceding analysis of task-specific data needs. These data domains, including master, inventory, economic and legal, and performance data, provide a structured yet adaptable framework for organizing essential building-related information. Each domain is further subdivided into data categories, which in turn serve as parent structures for specific data points (Figure 3.7). The taxonomy is designed for scalability, allowing for easy expansion by adding another digit to accommodate new data categories or attributes as needed.

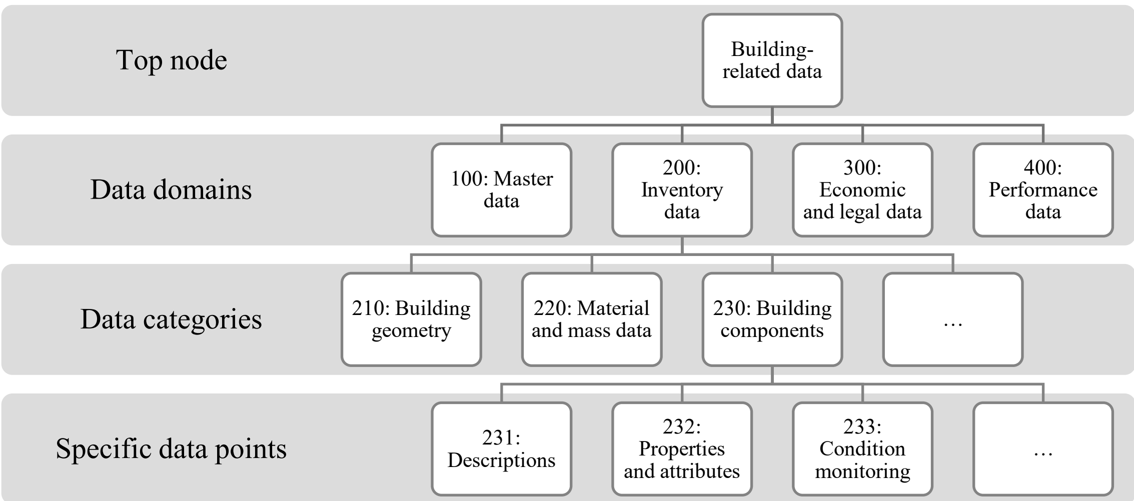



Figure 3.7: Extract from the taxonomy of building-related data

While the taxonomy serves as a structured representation of data needs, it should not be mistaken for a data model. Unlike a data model, which defines data semantics and relationships between data points, the taxonomy primarily functions as a classification system. Additionally, at this stage, the taxonomy does not establish explicit specifications regarding data quality. A detailed breakdown of the taxonomy including explanations of all categories can be found in section B.7.

#### 3.3.8.3 Master data

Within the taxonomy, master data provide a stable reference for structuring building-related information across different contexts. Unlike other data categories that frequently change due to operational updates or modifications, master data remain largely static and are only updated in specific cases, such as ownership transfers or regulatory reclassifications. Their primary function is to ensure consistent identification and classification of buildings and their key attributes, serving as a foundation for organizing other data categories.

A distinct categorization of master data is necessary because they establish unique identifiers, spatial context, and historical reference points that support information management across various systems. Identification data ensure unambiguous referencing, location data provide spatial positioning, and usage data define functional classifications. Ownership and actor-related information, along with planning and construction records, offer insights into legal, administrative, and processual aspects, while important dates document key milestones. By grouping these elements, the taxonomy provides a clear structure for master data (Table 3.10).

Table 3.10: Overview on master data categories in the taxonomy

| 100 | Master data |
|---|---|
| 110 | Identification |
| 120 | Building usage |
| 130 | Actor information |
| 140 | Important dates |
| 150 | Location and site data |
| 160 | Planning record |
| 170 | Construction record |
| 180 | Maintenance and usage log |
| 190 | Real estate management and transaction log |

Detailed explanations of master data categories can be found in section B.7.1.

#### 3.3.8.4 Inventory data

Inventory data capture the as-built status of a building from a physical-technical perspective, providing a structured basis for documentation, assessment, and management. This category ensures that geometric representations, material compositions, structural components, and technical systems are systematically recorded.

Building geometry establishes the spatial structure through floor plans, area classifications, and digital models, supporting planning, compliance, and integration with digital workflows. Material and mass data quantify volumes, distributions, and life cycle properties, relevant for structural assessments and sustainability considerations. Building components document physical and technical properties, ensuring traceability of materials, product documentation, and condition assessments.

Building services, including mechanical, electrical, and plumbing systems, are categorized separately due to their functional role in ensuring building operation. Similarly, furnishing and equipment, as well as fixtures and fittings, distinguish movable and semi-fixed elements contributing to usability. Outdoor facilities and room-related data provide structured information on external spaces and internal spatial configurations, supporting accessibility, navigation, and functional planning (Table 3.11).

Table 3.11: Overview on inventory data categories in the taxonomy

| 200 | Inventory data |
|---|---|
| 210 | Building geometry |
| 220 | Material and mass data |
| 230 | Building components |
| 240 | Building services |
| 250 | Furnishing and equipment |
| 260 | Fixtures and fittings |
| 270 | Outdoor facilities |
| 280 | Room (book) information |
| 290 | Functional building properties |

This categorization ensures that all physical attributes of a building and its surroundings are systematically structured and easily retrievable, forming a comprehensive reference for various technical and operational needs. Detailed explanations can be found in section B.7.2.

#### 3.3.8.5 Economic and legal data

Economic and legal data structure financial, ownership, taxation, and regulatory information related to a building. This category is distinct from inventory data as it focuses on cost structures, revenues, property valuation, legal rights, and contractual obligations rather than physical attributes.

Cost-related data include life cycle costs, operational expenses, and renewal investments, while revenue data account for income from leases, energy production, or material resale. Property valuation records document assessment methods and influencing factors. Ownership data and legal liabilities specify property rights, encumbrances, and easements, while contractual records cover agreements related to construction, financing, tenancy, and facility management. Regulatory compliance data include building permits, approvals, and compliance documents (Table 3.12).

Table 3.12: Overview on economic and legal data categories in the taxonomy

| 300 | Economic and legal data |
|---|---|
| 310 | Life cycle cost |
| 320 | Revenues |
| 330 | Property value |
| 340 | Taxes |
| 350 | Property rights and legal liabilities |
| 360 | Contracts |
| 370 | Building permits, approvals, and compliance documents |

By structuring economic and legal aspects separately, the taxonomy organizes financial and regulatory data relevant to real estate processes. Detailed explanations can be found in section B.7.3.

#### 3.3.8.6 Performance data

Performance data capture environmental, resource, and operational aspects of a building, serving as a basis for evaluations and documentation. This category includes energy use, emissions, environmental impacts, resource flows, and sustainability assessments, integrating both measured and calculated data.

A distinction is made between energy performance and emissions, reflecting operational efficiency and environmental effects. Resource-related data cover material use, waste, and circular economy aspects, supporting material efficiency considerations. Sustainability assessments document evaluation methods and certifications, while social and functional performance aspects address indoor environmental quality and user experience (Table 3.13).

Table 3.13: Overview on performance data categories in the taxonomy

| 400 | Performance data |
|---|---|
| 410 | Energy performance |
| 420 | Emissions |
| 430 | Environmental impact |
| 440 | Resource flows and efficiency |
| 450 | Sustainability assessment log |
| 460 | Social and functional performance |

These data are increasingly relevant not only for sustainability assessments but also in real estate management, valuation, and risk analysis, reflecting their growing importance in decision-making processes. Detailed explanations can be found in section B.7.4.

## 3.4 Issues in information management

As indicated by the substantial need for building-related data in the previous section, information plays a crucial role for the construction, operation and use of buildings throughout the life cycle- This aspect alone could be regarded as a strong incentive to improve the collection, maintenance, and exchange of building-related data for a majority of the involved actors. However, the high potential goes along with several issues that prevent significant improvements in the real estate industry. The underlying reasons will be identified in this section by systematically investigating issues in information management throughout the building life cycle. In particular, critical points for information management in the life cycle will be analyzed (section 3.4.1). Furthermore, problems that can be traced back on actors (section 3.4.2), the real estate industry as a whole (section 3.4.3), and data (section 3.4.4) will be analyzed. In addition, issues of principal-agent-theory in the real estate industry will be discussed (section 3.4.5). At last, a current state of existing explanations and solution approaches to the information problems will be given (section 3.4.6). Figure 3.8 provides a visual overview on these issues.

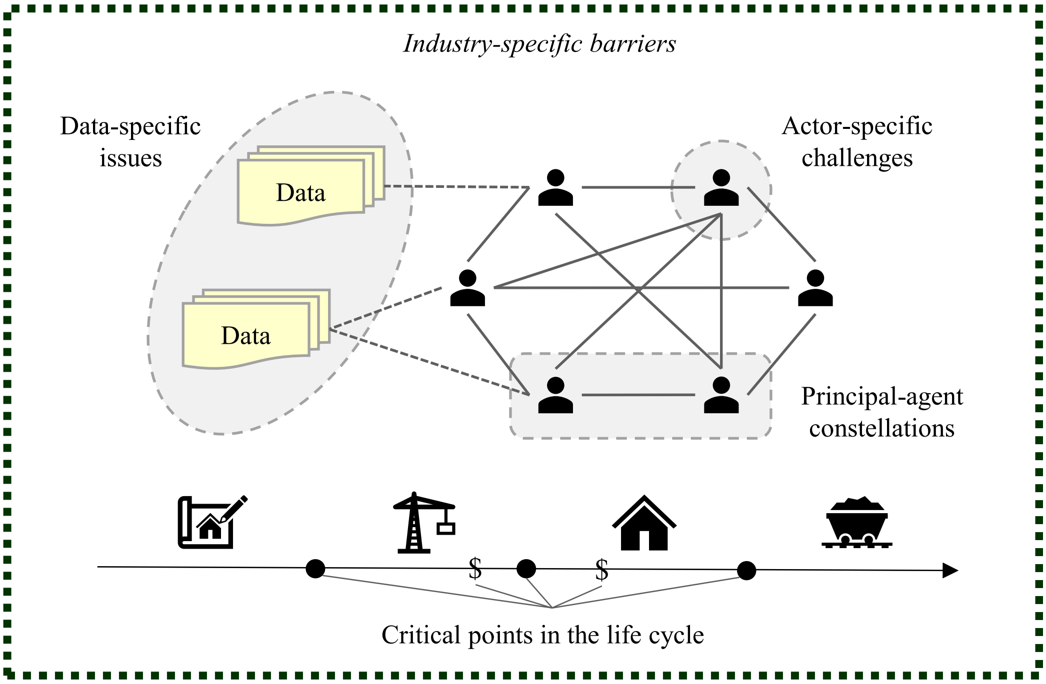



Figure 3.8: Overview on common issues in building-related information management

This section builds on relevant literature and selected insights from expert interviews (section B.1). While this section focuses on data-related and process-related issues in information management, the corresponding technical aspects will be addressed in chapter 4.

### 3.4.1 Critical points in the building life cycle

Transitions between life cycle stages present major challenges for data transfer, often due to shifting actors, missing incentives, and a lack of standardized conventions or supporting instruments. The literature speaks of media discontinuities when information is not transferred throughout life cycle stages (Kurzrock et al., 2019, p. 272). These media discontinuities prevent a continuous data retention throughout the life cycle (Mehlis, 2005, p. 271).

The transition from the development to the construction stage is often fluid, as no standardized definition distinguishes project development from construction. Managing building-related data becomes increasingly complex as project size and the number of actors grow. While communication and collaboration are emphasized for cost, time, and quality management, the structured transfer of data is often neglected. Several factors contribute to information management issues in this transition:

- Changing actors and responsibilities lead to insufficient data transfer.
- There is little incentive to retain data that is not immediately relevant for construction, often due to a lack of awareness of its future importance.
- Existing tools and frameworks do not sufficiently support the transfer of data into the next stage.

As a consequence, essential data from project development may not be available in later stages. In the worst case, even fundamental information such as user requirements or the building's basic structural concept may be lost.

The transition from construction to use is another critical point. Construction generates vast amounts of data related to building design, structure, and technical systems, yet ensuring that this knowledge reaches building owners and facility managers remains challenging. Regulatory frameworks and standards, as discussed in section 3.2.4, partly mandate documentation, but enforcement is inconsistent. The success of data transfer depends on contractual agreements, legal requirements, and the use of appropriate formats and tools. Several problems can be identified:

- No standardized conventions exist for the scope of handover documentation which is often inefficient and fragmented (Seaton et al., 2022, p. 29). Construction documentations as specified by HOAI, for example, are not legally binding and rarely commissioned.
- Builders often have no financial incentive to provide comprehensive as-built documentation.
- Building owners may not demand available data simply because they are unaware of its relevance, while, on the other hand, builders do not sufficiently take in the perspective of end-users.
- Few clear guidelines or criteria define which types of building-related data must be transferred (Zhu et al., 2021, p. 162).

Insufficient data and knowledge transfer at this stage has long-term consequences and is a general issue for the transition between projects and operations (Whyte et al., 2016, p. 3). Building owners may lack information on materials, durability, environmental performance, and maintenance requirements. Users might not have the necessary knowledge to operate building services effectively, and service providers, such as facility managers or craftsmen, often face challenges when planning modernizations or repairs due to missing data.

The final transition occurs between the use and end-of-life stages. With increasing attention to controlled deconstruction and material recycling, comprehensive documentation of a building's composition is essential. A reliable data foundation depends on prior data transfers from construction to use, as well as continuous updates reflecting modifications, wear, and maintenance. Challenges arise when:

- Previous data transfers have been incomplete, leading to gaps in available information.
- Relevant data from the use stage has not been documented or updated.
- Changes due to maintenance and renovations are not properly recorded.

When data are lacking, additional efforts for data collection become necessary before demolition or material recovery can proceed effectively.

Beyond these transitions, transactions introduce another recurring challenge for information management. Potential buyers require building-related data to assess whether a property meets their requirements, a need that applies to all types of buildings and ownership structures. However, current owners may be unable or unwilling to provide sufficient information, increasing uncertainty. For larger transactions, due diligence processes are used to compensate for missing data, but they are costly. Additionally, transactions are often affected by information asymmetries and principal-agent problems, as discussed in section 3.4.3.

## 3.4.2 Actor-specific challenges

### 3.4.2.1 Perception of necessity and benefits

Issues in information management are often interrelated with the decision-making of actors. Actors can actively or passively refuse to create, collect, maintain, or exchange data. They eventually do not perceive the necessity or benefits of actively engaging in building-related information management. This has several potential reasons:

- Long-term character of information management: Since creation and demand of building-related data are often temporally distributed, the costs and benefits are often distributed too. Building-related data can have a lifespan of several decades (Jaskula et al., 2022, p. 6). Actors weigh the benefits of managing building-related data much less if they lie far ahead.
- Quantification of costs and benefits: It is difficult for actors to quantify the benefits of having building-related data available in the right quality. It can be even more difficult to monetize these benefits which makes it harder to compare costs and benefits. Costs might be easier to quantify and monetize, but even here, actors struggle to evaluate non-monetary costs, e.g. time and effort for data collection.
- Uncertainty of development of costs and benefits: In connection with the long-term character of information management, actors perceive a lack of predictability of costs and benefits, which is a barrier to them. Also, the risks and opportunities often have not found a place in risk management and strategic planning.
- Abstract character and missing integration with operating business: Even if managing building-related data more sophisticatedly is seen as a rational choice, other barriers might prevent a stronger integration in real estate management.

Additional to factual reasons, psychological factors influence information management. Especially when it comes to data sharing and communication, actors may consciously or unconsciously refuse or reject to engage in this process. These decisions are influenced by emotions and motivation. If actors decline communication consciously, this can among other things be explained by the phenomenon of principal-agent-theory (section 3.4.5). A popular example for psychological reasons against communication in the real estate industry is given by the so-called vicious cycle of blame. The underlying concept is based on the fact that interconnected actors within the industry blame other actors for not engaging in the planning, constructing, and using of sustainable buildings (Hartenberger et al., 2008, p. 3).

#### 3.4.2.2 Missing resources

The lack of adequate resources presents a significant barrier to effective building-related information management. Many actors face difficulties in creating, collecting, storing, and sharing data due to limited financial means, outdated or insufficient ICT infrastructure, a shortage of qualified personnel, and the absence of suitable tools. While not addressing information management in the narrow sense, but rather in a broader sense through digitalization, a recent survey among industry representatives revealed that 81 % identified insufficient personnel resources and 61 % identified high investment costs as key barriers (ZIA & EY Real Estate, 2023, p. 14). Without these foundational elements, the potential for efficient and comprehensive information management remains limited, hindering innovation and collaboration.

Moreover, the availability and accessibility of these resources vary widely across the real estate industry. Private homeowners and small landlords often face greater challenges compared to larger companies, which may have dedicated departments or external support for managing building-related data. Similarly, the role of an actor within the building life cycle, whether as a developer, owner, tenant, or service provider, significantly influences their access to and reliance on such resources. Actors with greater exposure to or dependence on building-related data are more directly affected by these gaps.

#### 3.4.2.3 Process-related problems

Actor-specific problems can also be connected to the process of communication including data exchange and sharing. According to the sender-recipient model (section 2.2.2), there are at least two different actors involved in a communication. This helps explaining a couple of potential issues:

- Incorrect recipient: Data may be shared with the wrong actor, leading to delays or misuse of information.
- Incorrect sender: Information might originate from an unreliable or unauthorized source, reducing trust and accuracy.
- Lack of knowledge or errors in communication: Misunderstandings or insufficient expertise can result in incomplete or inaccurate data exchange.
- Absence of a common language or data model: Without standardized formats or shared terminology, actors may struggle to interpret or utilize the data effectively.

Additionally, communication in the real estate industry is rarely limited to a simple sender-recipient dynamic. Instead, it often involves multiple actors due to the complex actor constellations throughout the building life cycle. Many-to-many communication scenarios are common, further complicating data sharing processes. Without proper coordination and clear protocols, these scenarios can amplify the risk of miscommunication, data silos, and inefficiencies.

### 3.4.3 Industry-specific barriers

Industry-specific issues address the entirety of actors, established structures, framework conditions, and conventions in the real estate industry. Information management in the real estate industry is characterized through several factors: The political and regulatory framework refers to requirements on handling sensitive data, the disclosure of data, e.g. through building permits or sustainability reporting, or requirements on drafting contracts in construction projects. Standards can influence how actors create, collect, and share building-related data. Technological, societal, and economic developments can impact information management in the long run, while actor-specific information management also plays a role (section 3.4.2).

In the past, several industry-specific aspects have prevented a more sophisticated approach to manage building-related data:

- Fragmentation of standards and conventions: Different task areas throughout the building life cycle pose different requirements on managing building-related data. The industry uses an abundance of specific instruments related to satisfying their data needs even though many task areas rely on the same building-related data (section 3.3).
- Lack of business models and market mechanisms to manage building-related data: So far, actors are not sufficiently compensated for their investments in information management, since the demand side lacks the appropriate willingness-to-pay. This includes building owners among others, who do not commission the creation and collection of building-related data that are beneficial for real estate management throughout the life cycle. This leads to low financial incentives for supplier of data and information management solutions. Thus, business models rather focus on niche markets with specific task areas.
- Low levels of digitization and innovation: Digitization offers a lot of opportunities for information management, but the real estate industry is regarded as a slow adopter of new technologies (Klinc & Turk, 2019, p. 402).
- Lack of instruments and tools: The concept of a holistic BIS is still not widely distributed in the industry and further guidance and support is needed to stress their functionality and importance.

These aspects can add to typical information management issues that persist among actors and actor constellations (section 3.4.2).

### 3.4.4 Data-specific issues

Data are a key resource for information management processes. Throughout the life cycle of buildings, data are created, collected, stored, distributed, analyzed, altered, maintained, transferred, deleted, archived among other things. In all of these processes, data eventually does not meet the requirements of actors. This has several reasons:

- Missing, non-accessible data: One of the main problems occurs, when data are needed but are not available for actors in the building life cycle. Even if data are available to a certain extent, it might be that actors cannot find or access the data. Missing data results from the lack of creating, collecting, storing, or sharing data.
- False, incomplete, inconsistent data: Data can be false, incomplete or inconsistent as a result of imprecise data collection or intentionally misleading exchange of data. A sufficient quality control could eventually prevent this.
- Outdated, invalid data: Data might be out-of-date or invalid after changes to a building, for example after a modernization, or changes in the environment.
- Redundant data: If the same data are available multiple times, this can cause inefficiencies and lead to redundant work processes. Also, the maintenance and updating of data might complicate.
- Irrelevant data: Irrelevant data can lead to inefficiencies and cause misleading. Assessing the relevance of data can be difficult because data might be relevant for different actors at later stages in the life cycle.
- Incomprehensible data: If data are not represented in a proper way and format that the addressee is capable to handle, they are regarded as incomprehensible. Too large amounts of data can also lead to problems of comprehension.
- Insecure data: Tackling the insecurity that derives from data and related processes through appropriate measures gains importance in times of vast growing data amounts.
- Incompatible data: If data are incompatible to the user's systems or processes, problems occur for the accessibility and processibility of the data. The resulting interoperability issues can occur in the context of specific tools and systems
- Unclear governance and ownership of data: It is not always clear who has ownership of building-related data and, even more importantly, operational control. This issue is often accompanied by a lack of trust and missing data quality verification processes (Chamari et al., 2022, pp. 15–16; Hartenberger & Lorenz, 2017, p. 27; Hartenberger et al., 2021, p. 13; Jaskula et al., 2022, p. 7; Starzner et al., 2007, p. 99).

The listed data quality issues occur throughout the whole life cycle of buildings and pose substantial challenges to actors. They can be specific to certain data points and processes in the building life cycle.

### 3.4.5 Principal-agent theory and information asymmetries

Principal-agent theory (section B.8) helps to explain typical situations of information asymmetries in actor constellations and how both the principal and the agent act in these constellations. An information asymmetry occurs when a principal and an agent do not have the same level of information regarding an object of consideration. These situations persist throughout the entire economy whereas the real estate industry is specifically prone to them. Typical principal-agent constellations exist between buyer and seller of a building, landlord and tenant, or builders and project managers (Ceric & Ivic, 2021, p. 2451; Rohde et al., 2011, p. 19). Principal-agent constellations can have several negative consequences, such as:

- Decreased levels of building or service quality
- Loss of time and money, increased administration efforts, and additional costs
- Complaints, legal trials, and loss of trust (Lützkendorf & Speer, 2005, p. 186)

The reasons for principal-agent phenomena in the real estate industry can mainly be traced back to the heterogeneity and longevity of buildings and the low level of transparency within the market. A special feature in the real estate industry is that often both parties lack information about the respective building. In this case, none of the involved actors can make use of its role in the principal-agent constellation, but both are exposed to greater levels of risks (Rohde et al., 2011, pp. 19–20). Issues of principal-agent theory are basically a specific combination of several actor-specific (section 3.4.2) and data-specific problems (section 3.4.4).

Politics has recognized the downsides of information asymmetries in principal-agent constellations. Thus, it is one objective of new reporting obligations, such as the SFDR, to reduce these information asymmetries and increase transparency in the market with a focus on sustainability matters (SFDR, 2019, p. 10).

### 3.4.6 Impacts of poor information management

Deficiencies in information management can lead to a range of negative consequences for actors across the real estate and construction sectors. These consequences often intensify when multiple issues occur simultaneously or persist over time. Key impacts include:

- Financial losses and additional costs: Inaccessible, inconsistent, or lost data often requires regeneration or repeated collection efforts, leading to higher expenses for owners, users, and data providers.
- Increased risks and uncertainties: Incomplete or unreliable information impairs the ability to assess financial, legal, and environmental risks, resulting in less-informed and potentially flawed decision-making.
- Operational inefficiencies and productivity losses: Fragmented or poorly managed data impedes workflows in real estate and facility management, particularly when collaboration between multiple parties is required.
- Reduced trust in data and information flows: Inconsistent or unverifiable information diminishes actors' confidence in the validity and reliability of data, which can hinder cooperation and decision-making.
- Lack of transparency: Unequal access to information among stakeholders can lead to asymmetries that distort negotiations and decision processes, and may create room for unethical behavior or non-compliance.
- Difficulties in strategic asset and portfolio management: Without a sound and structured data foundation, it becomes challenging to define and implement coherent asset strategies or manage portfolios effectively.

- Missed opportunities for optimization: The absence of relevant or detailed data prevents the identification of performance improvements, particularly in building operation, renovation planning, and material or system reuse (Hartenberger et al., 2021, p. 13).

These effects highlight the critical need for improved information management practices to avoid inefficiencies, reduce risks, and unlock the potential of data-driven approaches across all stages of the building life cycle.

### 3.4.7 Summary of issues and solution approaches

The analyses in the previous sections have highlighted the broad spectrum of challenges associated with building-related information management. A central problem is that actors in the real estate industry often lack access to building-related data of adequate quality at the time it is needed for their respective tasks throughout the building life cycle. This issue is partly rooted in the specific characteristics of real estate and the industry itself, which contribute to substantial data losses at various stages of the life cycle. The effort required to obtain data in the appropriate quality is frequently high, while, at the same time, the value of systematic information management, particularly the timely and accurate collection of data, is often underestimated by actors when such data are or should be generated. As a result, the management of building-related data is often not prioritized to the extent necessary, and systematic approaches to information management remain underdeveloped or insufficiently implemented across the sector. These structural weaknesses are further exacerbated by typical information asymmetries and actor behavior, as described by principal-agent theory. In practice, poor information management can lead to financial losses, inefficiencies, increased risks, and missed opportunities for improving building and portfolio performance.

It seems unlikely that there is the one and simple solution to overcome the described problems. It rather needs a mix of certain actions in order to face the origins of these problems and to minimize their negative effects. In order to get a clearer picture of how potential solutions can be developed, Table 3.14 lists three categories for classification.

Table 3.14: Dimensions of information management solutions for the real estate industry

| Type of solution | Level of application | Degree of regulation |
|---|---|---|
| Improvement of process quality in information management | Individual and corporate level | Changes through regulation |
| Improvements of data quality | Real estate industry level | Changes through standards |
| Use of ICT | Economy level | Changes through market incentives |
| Use of assisting instruments and tools including BISs | | Changes through new or improved business models |

The focus of this thesis lies on one specific type of solution, namely BISs as an assisting tool for information management. The special characteristic of a BIS regarding the listed solution dimensions is that it can apply for several of these categories. For example, it can facilitate the improvement of data quality, the digitization of workflows, and the leveraging of new technologies at the same time. Figure 3.9 illustrates the potential of BISs regarding the aspect of continuous data retention throughout the life cycle. This continuity of managing building-related information compared to collecting data sporadically is regarded as one of the key aspects for the role of BISs.

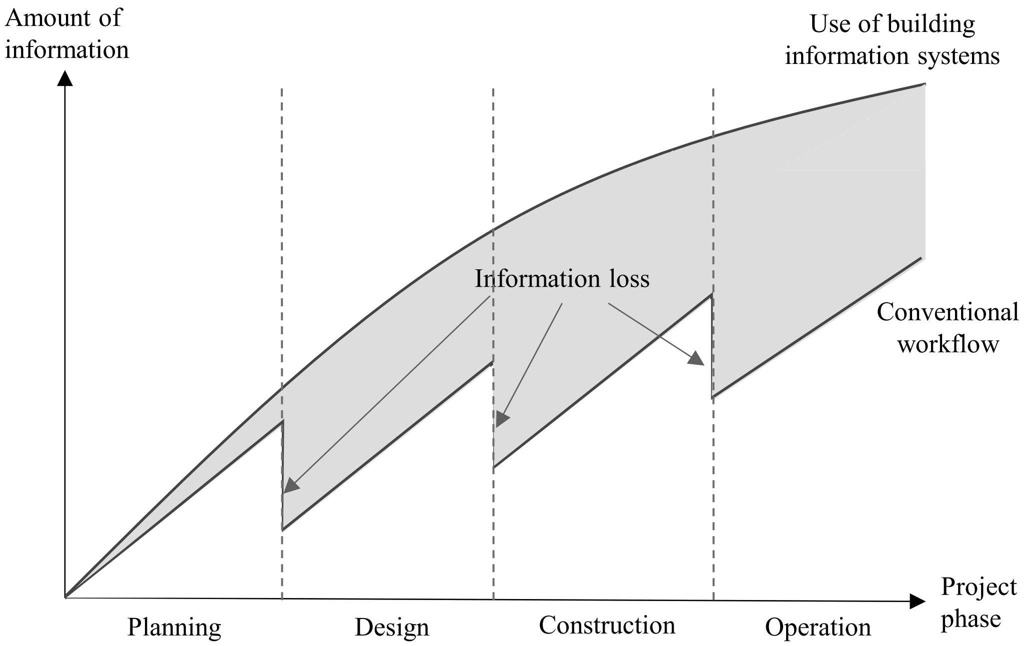



Figure 3.9: Amount of available information throughout the life cycle with the help of building information systems based on Sacks et al. (2018, p. 125)

The potentials of using BISs will be further deepened with the requirement profile in chapter 5.

## 3.5 Summary

Chapter 3 served to analyze information management throughout the life cycle of a building in order to derive requirements for a holistic BIS. The following findings were made:

- Building-related data are the currency of building-related information management. A definition of the term helps to navigate through the large amount of data that actors of the real estate industry are dealing with. According to this, building-related data should be understood as quality characteristics and properties that refer to single buildings. This includes static and dynamic data.
- Building-related data are created throughout the whole life cycle of buildings. There are multiple options to collect these data, if pursued, already at the timing of creation. Standards and regulatory frameworks make specifications which data should be collected, especially for the transition from construction to use stage.
- Throughout the whole life cycle, building-related data are needed by actors to fulfill their tasks. The approach to analyze task areas, their data needs as well as the similarities and differences in their data needs has not been used in the field of research until now. The analysis reveals that the need for building-related data is high, but that there are severe similarities for different tasks. The findings were used to develop a taxonomy of core data and documents for real estate management.
- The real estate industry suffers from significant challenges in information management. Building-related data are insufficiently available causing losses in efficiency and transparency, a decline in value creation, and additional costs. The reasons are manifold and can be attributed to the individual actors, their typical behavior, or the industry as a whole. At the same time, there are several ways for improvement whereas the focus in this thesis predominantly lies on BISs as assisting tools.

It becomes evident that there is a lack of life cycle-oriented, cross-task, and cross-actor data storage and maintenance. The findings from this chapter will serve as an essential basis for the requirement profile in chapter 5.

# 4 Technologies for managing building-related data

*Effective management of building-related data is essential for BISs across the building life cycle. As data complexity increases, digital technologies provide critical capabilities for collecting, storing, sharing, analyzing, and securing building-related information. This chapter examines these technologies, analyzing their potentials, challenges, and implications for BISs.*

*The chapter follows core stages of information management, among other things, assessing how data collection methods support structured and machine-readable formats (section 4.1), how storage solutions impact scalability and modularity (section 4.2), and how data sharing mechanisms enhance interoperability (section 4.3). It further discusses data quality management as an integral aspect across these processes (section 4.4), explores the role of data analytics in deriving value from building-related data (section 4.5), and evaluates data security strategies, including access control, governance models, and blockchain technology (section 4.6). The analysis highlights key interdependencies between these tasks, providing a basis for the requirement profile developed in chapter 5.*

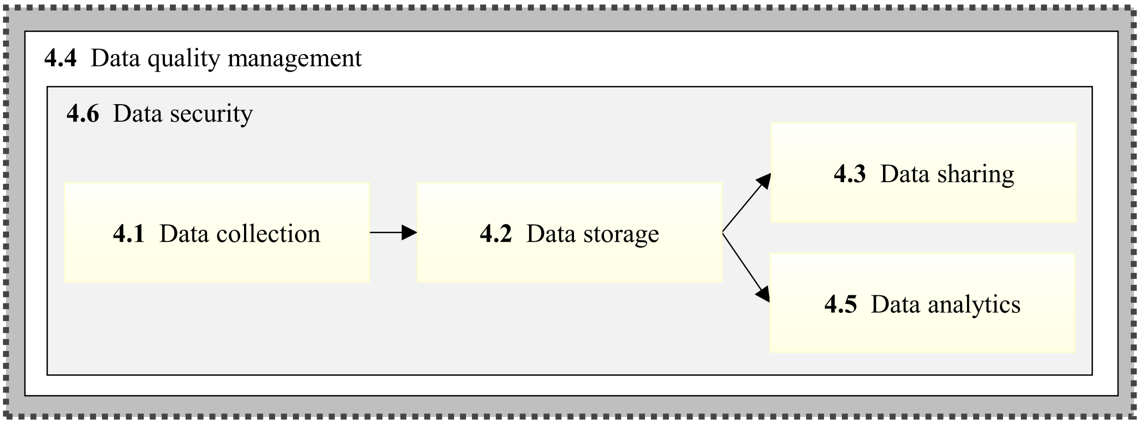



Figure 4.1: Structure of chapter 4

# 4.1 Data collection

Four main types of building-related data collection can be distinguished, serving as the basis for analyzing the respective ICTs.

| | **Original**<br>Directly from the source | **Secondary**<br>From existing sources |
|---|---|---|
| **Alphaumeric** | Direct entry of textual, numerical, or categorical data | Extraction or digitization of existing textual or numerical data |
| **Geometric** | Direct capture of spatial and geometric data | Reconstruction or conversion of existing geometric data |

Figure 4.2: Differentiation of different types of data collection

Original data collection is essential for building-related information management to reliably capture building attributes in reality. A differentiation can be made between original collection of geometric data, where spatial data are collected with the help of lasers, radars, or photos for example, and alphanumeric data, which refers to the direct entry of textual, numerical or categorical data and the capturing of real-time data through sensors, for example. Secondary data collection takes in a substantial role to leverage the potential of existing information sources and thus reduce the effort for original data collection.

## 4.1.1 Original collection of geometric data

Geometric data collection is experiencing changes through modern technologies. Traditional manual measurement approaches have largely been replaced by automated and sensor-based methods due to their labor-intensive nature and limited scalability. However, in certain niche applications, manual or semi-automated approaches still offer value where adaptability is required. Modern survey techniques, including photogrammetry, laser scanning, LiDAR, and radar, have been demonstrated to outperform traditional methods in terms of accuracy, efficiency, and cost-effectiveness (Olofsson et al., 2024, p. 14).

Despite their strengths, these technologies require careful consideration regarding their application. Differences in data accuracy, processing demands, and implementation costs affect their suitability for specific use cases. Photogrammetry is generally more accessible but depends heavily on lighting and surface texture. LiDAR and laser scanning provide high precision and dense point clouds but may entail higher costs and computational requirements. Radar, although less commonly used for above-ground 3D modeling in the built environment, can be valuable for detecting subsurface structures or in adverse weather conditions (Almukhtar et al., 2021, p. 216; Gordon et al., 2024, p. 43).

A more detailed overview on relevant technologies, their functionality, as well as the integrated ICTs and key considerations for their application can be found in Table C.1.

Geometric data collection technologies are typically not seen as part of BISs that store and manage the collected data afterward. They are rather processed in a way so that they can be transferred into BIM models and other digital representations. Therefore, the effectiveness of geometric data collection lies in its ability to provide accurate and structured information that can be seamlessly integrated into BISs. The interoperability of captured data is a fundamental requirement to ensure usability across various building life cycle stages.

Advancements in automation, such as standardized scan-to-BIM workflows, data cleansing techniques, and semantic enrichment, are improving the efficiency and accuracy of processing, enabling faster and more reliable data integration. However, despite these improvements, manual intervention is still often required, particularly for complex geometries and detailed object classification. This is especially relevant for building surveys of existing structures, where diverse conditions, legacy materials, and incomplete documentation pose additional challenges. The field remains highly dynamic, with ongoing efforts to further streamline workflows and enhance interoperability between data sources and BISs (Gordon et al., 2024, p. 45; Rashdi et al., 2022, p. 20).

### 4.1.2 Secondary collection of geometric data

The feasibility and efficiency of secondary collection of geometric data largely depend on the characteristics of the information source, particularly its degree of structuration and semantic depth. The less structured a source is, the greater the effort to extract usable geometric data (Soibelman et al., 2008, p. 16).

The least structured sources, such as paper-based blueprints, hand-drawn sketches, and physical models, require digitization as a first step. Scanning technologies convert hardcopy drawings into digital raster formats, but additional processing is needed to extract geometric information. Vectorization techniques, often supported by AI-based feature recognition, can convert raster images into structured vector formats. However, inconsistencies in the original documents, such as distortions, missing details, or outdated information, require data cleansing and manual correction before integration into digital environments. Substantial advancement in this field could be achieved within the last years through ML-based methodologies (Pizarro et al., 2022, pp. 1–3).

Digital 2D drawings, such as CAD files or scanned vector-based PDFs, offer a higher level of structuration but can lack semantic depth. While geometric relationships (e.g., lines, curves, and layers) can be extracted digitally, these formats do not necessarily provide standardized object-based representations or metadata (Mayer, 2018, pp. 304–306). Automated pattern recognition and rule-based interpretation can assist in identifying structural elements, but additional manual refinement is often necessary to ensure consistency and correctness. Advances in AI-driven classification methods are improving the ability to infer meaningful building components from such sources (Pizarro et al., 2022, p. 3).

Highly structured and semantically rich sources, such as IFC-based BIM models or GIS datasets, provide the most direct way to extract geometric data. These models explicitly define objects, spatial relationships, and metadata, allowing for structured querying and efficient data retrieval. The focus in secondary collection shifts from standardization, digitization, and processing toward interoperability and format conversion, ensuring compatibility between different systems (Costin et al., 2022, p. 24). While data consistency and versioning remain challenges, ICT solutions facilitate integration by leveraging application programming interfaces (APIs), data standards, and ontology-based mappings. These technologies will be further analyzed in the section on data sharing (4.3).

BISs need to integrate data quality requirements to ensure the reliable use of geometric data, which may also involve defining data models that specify integration requirements. Given the complexity of geometric data collection, specialized tools and systems are typically used for this purpose. These systems must be interoperable with BISs responsible for the long-term storage and management of geometric data, ensuring seamless data exchange and consistency across different applications.

### 4.1.3 Original collection of alphanumeric data

The original collection of alphanumeric data in buildings depends on the life cycle stage and the type of information required. During construction, data entries primarily serve documentation purposes, ensuring that execution aligns with design specifications. This includes material usage, work progress, and compliance records. While standard documentation tools are commonly used, ICT can improve efficiency by structuring data collection and integrating it into BISs. Wearable technology, for example, when worn by construction workers, offers real-time monitoring capabilities specifically for safety and health monitoring (Awolusi et al., 2018, p. 96), but is less relevant for capturing building-related data in a narrower sense. Radio Frequency Identification (RFID) and barcode tagging can be relevant technologies to collect building product data throughout the construction process depending on the situational requirements (Moselhi et al., 2020, p. 4).

During the use stage, alphanumeric data collection is primarily driven by sensor technology as part of technical monitoring (section 3.2.3.4). Sensors can facilitate non-destructive structural health monitoring by collecting data on the condition of building elements (Preethichandra et al., 2023). They are also key to determine resource flows and performance metrics that build on the measured values (Frei et al., 2020, p. 2). As part of Wireless Sensor Networks (WSNs) and Internet of Things (IoT) applications, sensors communicate with each other (Atta & Talamo, 2020, p. 269). These systems are increasingly applied in smart building infrastructures and integrated with digital twins to assess building performance and to manage building services (Kontaxis et al., 2022).

The benefit of sensor-based data depends on its integration into BISs, which must process, structure, and utilize them effectively. While sensors are essential for systems managing building operations, such as BAMSs and smart building solutions, their cost-benefit ratio within the real estate industry remains a critical factor (Arabshahi et al., 2021, p. 15). BISs must account for these economic considerations when integrating sensor-driven data collection. From a technical standpoint, data interoperability and the seamless integration of data points play a crucial role.

### 4.1.4 Secondary collection of alphanumeric data

For building-related information management throughout the life cycle, secondary collection of alphanumeric data is essential. Often, relevant building-related data already exist but are not in the right format, quality, or shared with the right actors. Technologies for secondary data collection not only support format transformation and quality improvements but also drive digitization, which is crucial for the application of BISs. The effectiveness of these technologies depends on the existing data format and quality, influencing their role in BISs.

While many collection processes in the industry still rely on manual methods, modern technologies enhance efficiency and integration. Optical Character Recognition (OCR) enables the digitization of scanned documents, converting analog text into searchable and structured digital formats (Kurzrock et al., 2023, p. 22). However, applying OCR to heterogeneous datasets remains a challenge, particularly in specific domains. New approaches combine OCR with AI and machine learning algorithms to improve accuracy and automate data structuring, further contributing to the digitization of building-related data (Raj et al., 2023, p. 651). The broader potentials of AI and computer vision are addressed in the context of data analytics (section 4.5).

Digitized data generated by OCR forms an essential basis for advanced information retrieval from unstructured sources. Using advanced search engines and Natural Language Processing (NLP) techniques, BISs can extract, interpret, and structure relevant information from extensive document repositories, considerably reducing manual effort and enhancing data accessibility. NLP-driven metadata extraction further improves usability, for example by automatically linking documents to related building elements, regulations, or operational information (Bilal et al., 2016, p. 511; Di Giuda et al., 2020, p. 98).

Secondary data collection also includes automated retrieval processes from external sources, such as web scraping for product databases or material properties (Hong et al., 2019, p. 237). Additionally, standardized querying mechanisms, for example in connection with semantic web technologies (section 4.3.2), allow BISs to access pertinent data points from existing datasets in real-time, ensuring the information remains actionable and up-to-date (Bonduel et al., 2022, p. 29). Whether integrated directly into BIS platforms or operating as complementary tools, these technologies play a pivotal role in making existing building-related data more structured, usable, and interoperable.

# 4.2 Data storage

Within this section, data storage solutions for building-related data in the context of BISs are analyzed. Four essential issues, that are closely linked to each other, are considered: the consideration of different storage paradigms (section 4.2.1), the specification of a data architecture (section 4.2.2), the suitability of different types of databases (section 4.2.3), and the choice between local and cloud-based storage approaches (section 4.2.4).

## 4.2.1 Architectural patterns and storage paradigms

Different architectural patterns offer distinct advantages and trade-offs for BISs, depending on their requirements for scalability, modularity, and control (Table C.2). These architectures can be used individually or in combination to address specific needs.

Client-server architectures enable centralized data storage and controlled access, ensuring data consistency and enforceable security policies. However, as the number of users and datasets grows, scalability can become a concern, requiring additional infrastructure or cloud-based solutions (Sunyaev, 2020, p. 36). BISs benefiting from structured data governance and secure access control can leverage this architecture effectively.

Tiered architectures enhance system modularity by separating functions across multiple layers. A two-tier model allows direct interaction between clients and data storage, whereas multi-tier architectures introduce intermediary layers for improved scalability and integration. While this improves flexibility and supports the integration of additional technologies, complexity increases with additional tiers (Sunyaev, 2020, p. 42). BISs requiring structured data processing, interoperability, or modular expansion can benefit from this approach.

Peer-to-peer (P2P) architectures facilitate decentralized data exchange without a central authority, making them suitable for collaborative environments where multiple actors contribute to and access shared data. This enhances data resilience, resistance against security attacks, while reducing single points of failure (Sunyaev, 2020, p. 44). However, these advantages come at the cost of increased complexity in replication mechanisms and metadata exchange (Krcmar, 2015, p. 347), as well as potential limitations due to typically lower computing power of peers compared to dedicated servers and often poorer connection quality among peer nodes (Hansen et al., 2019, p. 612). P2P can be useful for BISs in distributed project environments or multi-stakeholder data-sharing scenarios.

Microservices architecture, which evolved from service-oriented architecture (SOA), represents a specialized pattern increasingly used in modern information systems to enhance scalability and flexibility. Unlike monolithic systems, which bundle functionality into a single, tightly integrated application, SOA structures systems into loosely coupled, interoperable services, and microservices further decompose these into fine-grained, independently deployable units communicating via APIs (section C.3.4). This architectural shift allows selective scaling, easier updates, and integration of diverse technologies, but also introduces complexities in service orchestration, data consistency, and inter-service communication (F. Auer et al., 2021; Bushong et al., 2021; Söylemez et al., 2022). BISs managing diverse functions, evolving requirements, or large-scale integrations can particularly benefit from microservices, provided robust service interaction management is ensured."

Figure 4.3 illustrates a typical microservices architecture, highlighting the interaction between client applications, the master node for orchestration and discovery, and distributed execution across multiple service nodes.

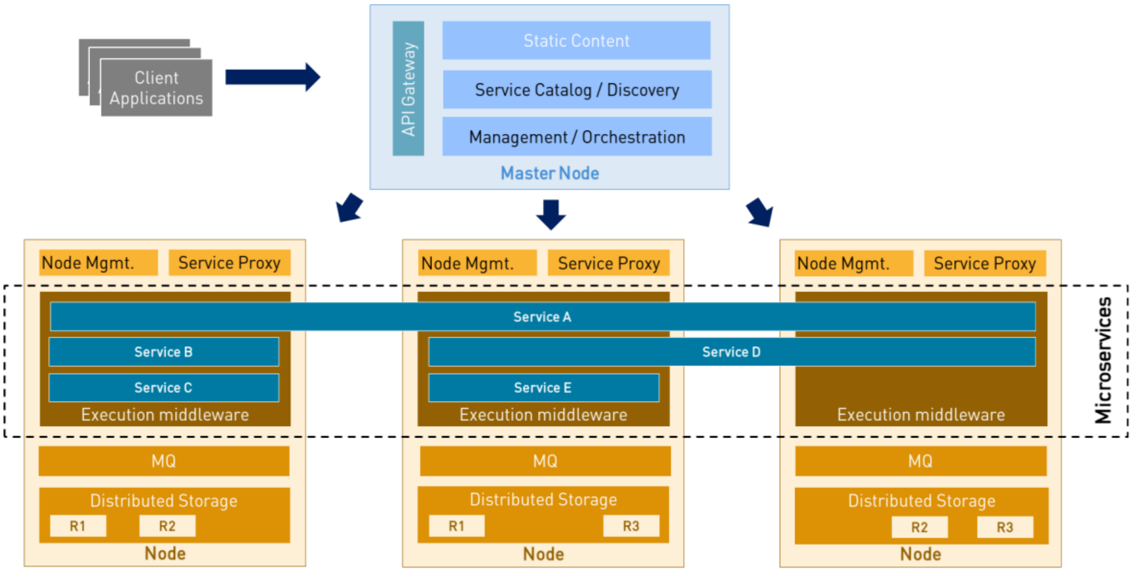



Figure 4.3: Example for a microservice architecture (Kehrli, 2021)

One critical decision in designing BISs is the choice of data storage architecture. Storage paradigms define how data are physically stored and managed across systems (Table C.3). Centralized storage offers simplicity and direct control but introduces scalability limitations and single points of failure. Decentralized storage models improve resilience by distributing data across multiple nodes, though they require more complex integration and synchronization strategies. Federated storage, particularly relevant for BISs, enables unified access to distributed datasets while preserving the autonomy of different data sources. Each approach has trade-offs. Centralized systems may be suitable for smaller-scale BISs or cases where strict access control and governance are prioritized. Parallel and distributed models enhance processing efficiency and scalability but rely on robust network infrastructure. Federated systems allow heterogeneous data integration across different actors and systems, making them well-suited for BISs that handle diverse building-related datasets. However, their implementation involves higher complexity in integration and data consistency management (Rahm et al., 2015, pp. 43–74). In Table 4.1, key aspects to consider for the different storage paradigms are summarized.

Table 4.1: Paradigms for storage of digital data

| Storage paradigm | Advantage | Disadvantage |
|---|---|---|
| Centralized Storage | Simple to manage, high control over data, ease of setup | Single points of failure |
| Parallel Systems | Fast transactions, scalable processing, efficient resource use | Dependency on high-speed network infrastructure |
| Distributed Systems | Resilient, scalable, autonomous nodes reduce single points of failure | Complex synchronization |
| Federated Systems | Unified data access, supports heterogeneous systems, preserves local autonomy | High integration complexity |

It is important to note that the choice of a data storage paradigm is not always fully within the control of BIS developers or software designers. Often, it is influenced by factors such as the type of application, pre-existing technology stacks, and platform constraints. For instance, cloud infrastructures typically favor multi-tier or hybrid setups, while traditional systems may enforce centralized paradigms. In some cases, regulatory requirements or budgetary limitations further narrow the available options. Understanding these paradigms, however, provides a conceptual framework that helps decision-makers select the most suitable technologies within their constraints.

For BISs, the storage paradigm significantly influences scalability, reliability, and interoperability. These requirements shape the design of data structures, influencing decisions between centralized, decentralized, or federated approaches. Decentralized and federated systems appear especially promising for handling the diverse and distributed nature of building-related data. However, centralized systems may still play a role in certain contexts, such as smaller-scale projects or where simplicity is prioritized.

### 4.2.2 Data architecture

In the context of BISs, data architecture refers to the conceptual and structural organization of data, how data are described, related, and made accessible. It is distinct from data infrastructure, which primarily focuses on physical storage technologies and system architecture at the hardware or platform level (Inmon et al., 2019, p. 7). While data architecture is sometimes used interchangeably with data modeling, it extends beyond individual models by addressing the broader semantic and organizational context in which data are created, maintained, and used. As such, it plays a critical role in designing systems that support high-quality, interoperable, and long-lived data.

The relevance of data architectures for BISs lies in their ability to support structured data exchange, consistent interpretation, and alignment with the needs of diverse actors. They offer a foundation for managing both structured and semi-structured data and guide the development of underlying models and implementation formats.

A useful reference framework is provided by the ISO 8000 standard series, which emphasizes the role of data architecture in preserving data quality in data sharing. Building on this, Böhms et al. (2023, p. 10) propose a set of key elements tailored to building-related data contexts:

- Data specification: Defines the structure and semantics of building-related data, ensuring that data can be interpreted correctly within the system.
- Data dictionary: Provides a standardized terminology, ensuring consistent definitions and reducing ambiguity in data exchange.
- Data specification/dictionary language: Enables a standardized modeling approach, forming the basis for logical and physical data implementation.
- Formal syntax: Ensures that the data model can be expressed in a machine-readable format, facilitating automated processing and exchange.
- Identification scheme: Establishes unique identifiers for data elements, enabling reliable referencing and linking of information across systems.
- Metadata: Describes contextual attributes of data, such as provenance and quality indicators, supporting data governance and usability.

These elements enable the translation of conceptual models into logical and physical representations, such as database schemas or exchange formats. They also help bridge the technical structure of ICT systems with the semantic and practical needs of building-related information management. While not yet widespread in the real estate industry, architectural thinking is implicitly present in many initiatives that aim to standardize building-related data (section 4.3.3).

### 4.2.3 Database technology

There are two main aspects to consider when designing data storage systems for building-related data. First, the projected function of the BIS must be determined. This includes understanding how data will be used, the frequency and complexity of transactions (e.g., storing, editing, and deleting), the anticipated query patterns, the number of simultaneous users, and the performance and capacity requirements. These factors underscore the importance of integrating storage design into the overall architecture of the BIS from the outset. Second, the characteristics of the data itself must be carefully considered. Building-related data are highly diverse, encompassing structured alphanumeric data (e.g., compliance documents, sensor readings) and unstructured data (e.g., geometric models, images, videos).

Database technology (section C.2.3) plays a critical role in managing building-related datasets, encompassing structured, semi-structured, and unstructured data. The choice of database type influences data accessibility, scalability, and long-term usability. While relational databases remain widely used due to their structured approach and well-established standards, they can be rigid when handling evolving data structures. BISs can also accommodate more flexible data models:

- NoSQL databases, including document databases and graph databases, offer scalability and flexibility, particularly for integrating heterogeneous building-related data. Document databases are useful for storing metadata and interconnected records, while graph databases excel in representing complex relationships, such as linking building components across life cycle stages (Bilal et al., 2016, p. 504).
- Spatial databases are essential for GIS-related applications, such as mapping building layouts and georeferencing infrastructure data (Brinkhoff & Kresse, 2022, p. 70).
- Data lakes provide an alternative for handling large, unstructured datasets, offering a repository for poly-structured data that can be processed later. However, they require strong data governance to avoid becoming "data swamps" with unmanageable content (Hernández et al., 2023).

The suitability of a database model for BISs depends on factors such as data structure, integration needs, and performance requirements. In many cases, hybrid database models, combining relational and NoSQL features, provide a balanced approach, offering both structured querying capabilities and flexible data handling. Emerging trends, such as cloud-based database solutions and blockchain-backed data integrity mechanisms, further influence database selection for BISs.

### 4.2.4 Cloud vs local storage systems

A critical consideration is whether a local or cloud-based storage system is better suited for a BIS. Local storage systems offer high levels of control, allowing organizations to manage their data on-premise with minimal reliance on external providers. They are particularly suited for environments where data sovereignty, security, or low-latency access are paramount. However, they require substantial IT infrastructure, ongoing maintenance, and scalability investments, which may pose challenges for smaller organizations or those with limited technical expertise.

In contrast, cloud computing is regarded as a vehicle for innovation in the construction and real estate industry (Bello et al., 2021, p. 1). Cloud-based storage systems provide scalability, cost-efficiency, and ubiquitous access, making them particularly advantageous for BISs that integrate data from geographically distributed sources, such as IoT devices or multi-actor projects. Cloud solutions also offer built-in features for backup, disaster recovery, and dynamic scaling, reducing operational burdens on users. However, they may raise concerns about data sovereignty, location transparency, and long-term dependency on cloud providers. For a detailed overview of cloud computing principles, service models, and key characteristics, see section C.2.2.

The choice between local and cloud storage is not purely technical but also depends on the actors involved and their capabilities. Large enterprises and public sector organizations with strict regulatory requirements may favor local or hybrid solutions to maintain control over sensitive information. Smaller companies or decentralized projects may benefit more from cloud-based storage, as it lowers IT management overhead and provides flexible access to resources.

A hybrid storage approach, which combines local control with cloud scalability, can address these challenges. Sensitive data or compliance documents can be stored locally for security and sovereignty, while less sensitive or large-scale data (e.g., sensor outputs, simulation results) can be stored in the cloud for improved accessibility and scalability.

# 4.3 Data sharing

Effective data sharing is essential for ensuring interoperability, collaboration, and structured information management in BISs. Given the diversity of actors, systems, and life cycle stages, seamless exchange of building-related data remains a challenge. This section examines different aspects of data sharing, beginning with data formats (section 4.3.1), which determine how structured and unstructured data can be exchanged and integrated. Linked Data and Semantic Web technology (section 4.3.2) provide a framework for machine-readable, interconnected datasets that enhance interoperability. In parallel, building-related data standards (section 4.3.3) establish common frameworks to ensure data consistency across processes and systems. Finally, platforms and data rooms (section 4.3.4) serve as digital environments that facilitate collaboration and controlled data exchange across stakeholders.

## 4.3.1 Data formats

Data formats are critical for successful communication in the real estate industry. They serve as the language through which IT systems interact, and their effective use determines the quality and efficiency of data exchange. The development of data formats in the real estate industry is closely connected to advances in data and information modeling, reflecting the increasing complexity of building-related information and the need for versatile approaches to ensure interoperability (Borrmann et al., 2024). The variety of formats ranges from structured data for machine processing to unstructured documents for human interpretation. Several commonly used data formats were identified and analyzed regarding their key characteristics, strengths, weaknesses, and potential use cases for building-related data and BISs (Table C.6).

Structured formats like XML, JSON, and IFC are established in the real estate industry for exchanging structured building-related data. XML (Extensible Markup Language) is valued for its versatility and ability to represent hierarchical data structures in a machine- and human-readable form (Salminen, 2011, pp. 1–4). Its schema validation capabilities ensure data consistency across systems, making it a quasi-standard for collaborative software development and data interoperability (Salminen, 2011, p. 69).

JSON (JavaScript Object Notation), in contrast, is a lightweight alternative that simplifies data exchange, particularly in web-based applications. Its simplicity and speed have contributed to its growing adoption, as seen in international initiatives for real estate data models like the International Building Performance & Data Initiative (IBPDI) and OSCRE (IBPDI, 2022b; OSCRE International, 2022).

The Industry Foundation Classes (IFC) format, central to BIM applications, provides a schema for representing both geometric and semantic data about buildings. Based on the EXPRESS modeling language (section 2.3.3), IFC supports object-oriented representation of building components and their relationships (DIN EN ISO 16739-1:2021-11, p. 7). It potentially supports data sharing across life cycle stages with a particular focus on geometric data. Its extensibility and support for multiple formats (e.g., XML, JSON) allow for greater interoperability. To address the growing integration of digital building models with broader life cycle data, IFC also offers property sets that enable semantic enrichment, although challenges remain due to the lack of standardization in their use (Borrmann, Beetz, et al., 2018, pp. 101–114).

In addition to structured data formats, document formats like PDFs, Word files, and scanned images remain indispensable for nearly all actors in the real estate industry. While these formats are typically human-readable, some formats, such as XBRL, integrate structured data to support both human and machine readability. This approach is particularly useful in domains like financial reporting, where regulatory compliance demands interoperability and accessibility for diverse stakeholders (Hoitash et al., 2021, pp. 109–110). For long-term archiving, PDF/A provides a standardized version of PDF, ensuring that documents remain accessible and unaltered over time by embedding fonts, restricting certain interactive features, and requiring metadata compliance (Kurzrock et al., 2023, p. 15).

To meet the diverse requirements of building-related information management, formats must support the coexistence of structured data and documents to ensure interoperability across systems and life cycle stages. The choice of format should be guided by the data's characteristics, quality requirements, and context of use, ensuring accessibility and reliability over time.

### 4.3.2 Linked data and semantic web technology

The adoption of Linked Data (LD) and Semantic Web (SW) technologies has introduced significant advancements in data sharing and interoperability within the real estate industry. These technologies have driven the development of innovative data formats, vocabularies, and methodologies, enabling more structured and integrated information management. Given its diverse actors and fragmented data systems, the real estate industry is particularly poised to benefit from LD/SW's interlinked, machine-readable data, which facilitates seamless data exchange (Pauwels et al., 2017, p. 147).

LD/SW technologies rest on foundational concepts such as RDF, OWL, and SPARQL, which enable the modeling, querying, and reasoning of structured data. Section C.3.2 provides an overview of RDF principles and serializations.

A key distinction of LD/SW technologies lies in their focus on machine-processable semantics and decentralized data integration. Unlike traditional data formats, which often rely on centralized schemas and rigid structures, LD/SW promotes a scalable and flexible approach to data modeling and sharing through RDF-based vocabularies and ontologies. This paradigm shift enables the integration of heterogeneous data sources while maintaining semantic coherence, a critical requirement for BISs operating in dynamic, multi-actor environments (Costin et al., 2022, pp. 23–24).

While LD/SW applications in real estate are relatively recent, they are rapidly expanding. Industry-specific initiatives leverage LD principles to create ontologies that enhance semantic interoperability across systems. This has the potential to bridge data silos, improve data quality, and support advanced use cases, such as cost estimations in building models, management of maintenance data, retrieval of sustainability-related data from the web, or knowledge inference for construction code compliance (Farghaly et al., 2023, pp. 4–8).

In the context of BISs, LD/SW technologies offer key advantages, including the ability to model complex relationships, ensure data consistency, and facilitate reasoning. However, challenges remain, particularly concerning the need for specialized expertise, ontology development and standardization complexities, scalability and performance issues, vendor cooperation, and effective governance mechanisms to ensure sustained adoption and interoperability (Costin et al., 2022, p. 23; Pauwels et al., 2017, p. 160). Ongoing research addresses these challenges and, for example, explores the integration of LD/SW technologies with common building-related data standards, and emerging technologies like AI.

### 4.3.3 Building-related data standards

Efforts to improve data sharing and interoperability in the real estate industry go beyond the discussion on data formats and increasingly focus on establishing common standards. These standards aim to provide a unified language for representing and exchanging building-related data, ensuring consistency across actors, processes, and life cycle stages. A key objective is often the standardization of semantic descriptions, such as building dimensions, properties, attributes, and relationships between components. These are sometimes referred to as metadata standards for buildings. The standards analyzed in this section include contributions from both international and national standardization committees as well as industry initiatives. Their variety highlights the diverse needs of actors and tasks throughout the building lifecycle but also underscores the difficulty in achieving harmonization.

In total, 12 standards were identified and analyzed, with a comparison provided in section C.3.3. The analysis considered the following criteria to evaluate the suitability of each standard for BISs:

- Primary use case: The standard's focus on specific real estate industry tasks or workflows, such as building operations or property management.
- Interoperability: The ability of the standard to seamlessly integrate and exchange data with other systems and standards.
- Semantic richness: The depth of metadata and relationships represented within the standard, enabling advanced reasoning and linking of data.
- Flexibility: The adaptability of the standard to support evolving use cases and changes in data requirements.

The analysis highlights strong interoperability and semantic modeling capabilities among industry-driven standards, particularly those leveraging RDF and OWL. However, limitations in life cycle coverage and practical adoption across diverse use cases indicate that it is difficult to assess if a single standard is currently advantageous for BISs.

Among industry-driven standards, the RealEstateCore ontology is designed to support the integration of different types of building-related data. Using RDF and OWL, it defines relationships among building components and systems, enabling semantic interoperability and advanced reasoning (RealEstateCore, 2023). While RealEstateCore demonstrates strong operational focus and semantic richness, its life cycle coverage remains limited. Similarly, BrickSchema provides a modular approach for representing physical, virtual, and logical entities.

Focusing on building services and operational data, BrickSchema demonstrates high semantic depth but primarily addresses building operation phases (Brick Consortium, 2023).

The OSCRE Industry Data Model targets over 130 use cases, including property management and facility operations. Implemented in JSON and XML, it offers flexibility but is constrained in life cycle scope and semantic capabilities (OSCRE International, 2022). The IBPDI Global Data Model proposes a unified data model for real estate, offering definitions for properties, geometric representations, and financial data. Published in JSON, it aims to cover all life cycle stages but remains in early adoption stages (IBPDI, 2022a). Other notable initiatives include the RESO Data Dictionary for real estate agents, OpenImmo for property listings, and the Society of Property Researchers' guidelines for building life cycle data exchange (OpenImmo, 2022; Real Estate Standards Organization [RESO], 2023; gif, 2021).

What most of these standards have in common is their limited adoption among industry practitioners, potentially due to their technical complexity, structural rigidity, and integration challenges. Many actors lack the technical expertise or resources required for full implementation, while fragmented industry practices further complicate broad adoption.

Among standards developed by committees, the IFC stand out due to their prominence in the construction and real estate sectors. Originally developed by buildingSMART and later standardized by ISO, IFC provides a schema for representing building-related entities and their relationships. Uniquely, IFC is regarded as both a data format and a data standard, bridging technical and semantic interoperability challenges in BIM-based workflows (DIN EN ISO 16739-1:2021-11, p. 7).

Complementary to IFC, the Construction Operations Building Information Exchange (COBie) standard aims to standardize the exchange of non-geometric building data, particularly for facility management. By structuring asset information in various formats, including spreadsheets, XML, and IFC, COBie aims to enhance interoperability between BIM and operational systems. However, adoption challenges persist, as its technical complexity can be daunting for facility management personnel, necessitating comprehensive training and integration efforts (Vishal Kumar & Teo, 2021, pp. 339–341).

While committee-driven standards, such as those developed by ISO and DIN, play a crucial role in harmonizing data exchange processes, their breadth and technical nature can create challenges in industry-wide adoption. A summary of key committee-driven standards and their relevance to BISs is provided in Table C.8.

The analyzed standards provide a strong foundation for structured data in BISs, fostering interoperability and consistency when applied correctly. Ontology-based approaches further extend these capabilities by enabling semantic integration of semi-structured data, supporting more flexible data representations. However, challenges remain in handling heterogeneous data, which is prevalent in many building-related workflows. Additionally, the technical complexity of these standards often exceeds the expertise of non-specialist actors, limiting their practical implementation. To fully leverage their potential, efforts toward simplifying application, improving accessibility, and integrating ontology-driven methods could enhance their relevance for broader industry adoption.

### 4.3.4 Platforms and data rooms

The increasing complexity of real estate management requires intensive communication and data exchange among diverse actors. This has driven the development of internet-based platforms designed to facilitate collaboration, improve data accessibility, and enhance decision-making in comparison to traditional, local file-based methods. These platforms, often referred to as “digital platforms” (Reuver et al., 2018, p. 124; Seaton et al., 2022, p. 37) or “data rooms” (Kurzrock et al., 2019, p. 275), provide structured environments for managing and sharing building-related data. Their degree of confidentiality and security measures varies depending on the use case, ranging from open collaboration environments to highly secure data rooms for sensitive transactions. Beyond enabling data sharing, many platforms integrate features that assist users in processing, analyzing, and visualizing data, catering to their specific tasks. This trend aligns with the broader concepts of "platformization" (Sunyaev, 2020, p. 219) and "ecosystems" (Ditfurth et al., 2021, p. 7; Zielinski, 2022, p. 89) observed in the industry, where interconnected platforms aim to foster collaboration across actors and domains and provide central services.

Table 4.2 provides an overview of key platform and data room types, highlighting their primary use cases and typical features in the real estate and construction industries.

Table 4.2: Overview on common platforms and data rooms in the real estate domain

| Use case | Primary purpose | Typical features |
|---|---|---|
| Project management platforms / data rooms (construction) | Facilitate collaboration, document sharing, and communication among project stakeholders | Task tracking, version-controlled document storage, real-time chat, permission-based access |
| BIM platforms & common data environments (CDEs) | Centralize BIM data and coordinate project models (discussed in more detail in section 6.4) | Model versioning, clash detection, federated model integration, role-based access |
| Due diligence data rooms | Secure storage and controlled access to legal, financial, and technical documents for real estate transactions | Encrypted storage, audit logs, role-based access, document expiration settings |
| ESG & sustainability platforms | Support sustainability reporting, compliance tracking, and energy renovation planning for example (discussed in more detail in section 6.5.2.3) | Data dashboards, automated compliance checks, regulatory frameworks, impact visualization |
| Smart building & IoT platforms | Enable real-time monitoring, automation, and optimization of building operations | Sensor data processing, AI-driven analytics, predictive maintenance, digital twins |

Modern platforms rely on several key technologies to ensure scalability, interoperability, and security:

- Cloud infrastructures (section C.2.2) provide scalable storage and remote access capabilities.
- APIs (section C.3.4) enable integration with external tools and data sources.
- Data security technologies, including encryption and private (hardware) keys, ensure confidentiality in highly secure data rooms (see section 4.6 on data security).

While platforms and BISs share common functions, they do not necessarily serve the same roles. Platforms primarily act as enablers of data sharing and collaboration, offering structured environments for specific use cases. BISs, on the other hand, encompass a broader concept designed to support building-related information management. In many cases, BISs integrate platform characteristics to facilitate data integration, interoperability, and accessibility, leveraging cloud infrastructures, APIs, and federated storage approaches. The platformization of BISs may enhance their ability to connect actors, standardize data exchange, and enable structured workflows. Platforms themselves can be regarded as BISs as long as they integrate common BIS characteristics, as defined in section 2.4.1.

## 4.4 Data quality management

High data quality is essential for the effective operation of BISs, as inaccurate, incomplete, or inconsistent data can undermine decision-making and system functionality (sections 3.4.4 and 3.4.6). More than 70% of real estate companies consider a lack of data quality to be a critical factor preventing further digitization, according to a recent survey (ZIA & EY Real Estate, 2024, p. 13). While many researchers and practitioners consider data quality to be an important issue in specific subject areas, there is little literature that systematically addresses the management of building-related data quality. In this section, the factors influencing building-related data quality are therefore examined first (section 4.4.1). Based on this foundation, measures for managing data quality are analyzed (section 4.4.2).

### 4.4.1 Factors shaping building-related data quality

Data quality is a fundamental requirement for BISs, directly impacting the accuracy, reliability, and usability of building-related information across the building life cycle. High-quality data supports informed decision-making, regulatory compliance, and operational efficiency. Dimensions such as accuracy, completeness, consistency, and traceability serve as objectives for ensuring reliable data management, with a more detailed explanation of data quality dimensions provided in section C.4. However, data quality is not static. It is shaped dynamically by various influences (Bodenbender & Kurzrock, 2015). These influences emerge throughout information management tasks including data collection, storage, sharing, and analysis (Figure 4.4).

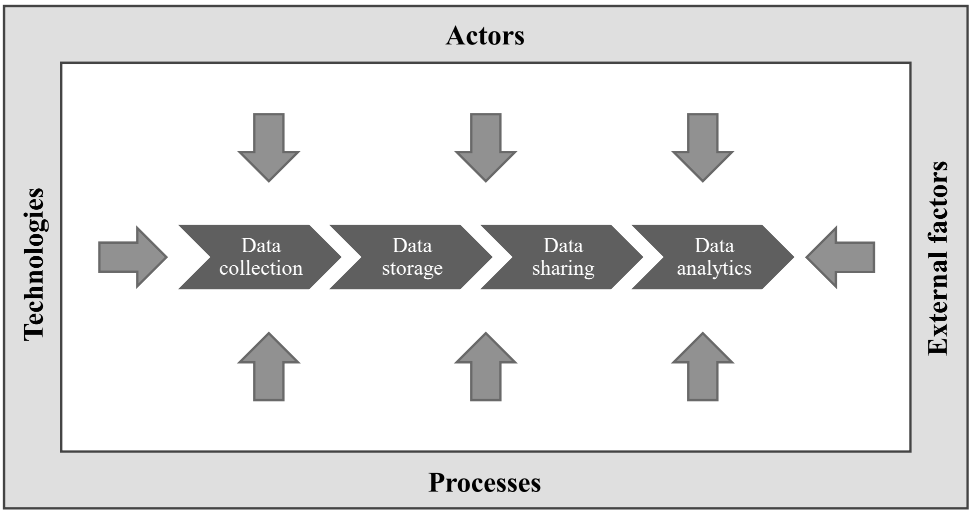



Figure 4.4: Overview on factors influencing building-related information management

Actors play a crucial role in maintaining data quality, even as technological advancements assist in preserving and restoring it (Murphy, 2009, p. 1881). Individuals remain responsible for ensuring data are handled correctly, with expertise and decision-making significantly affecting accuracy and completeness. The variety of tasks and building-related data points in the real estate industry requires diverse expertise, as specialists must collaborate to ensure data remain valid and usable across different tasks. Errors in manual entry, misinterpretation, or a lack of verification mechanisms can undermine quality, while governance structures and responsibilities define whether data remains structured and traceable. Even when data processing is automated, the effectiveness of technological measures depends on how they are implemented and monitored by human actors.

Processes are closely linked to the role of actors in data quality management, as they define workflows and organizational structures in which data are generated and managed (Weigel, 2021, p. 79). Complex projects and multi-actor collaborations increase the challenge of maintaining structured and consistent data. High process quality ensures clear responsibilities and structured data flows, while weak governance structures increase the likelihood of fragmentation, inconsistencies, and data loss.

Technology plays a central role in shaping data quality within BISs by providing the structural and computational foundation for handling building-related data. It determines how data are captured, structured, stored, and accessed, influencing key dimensions such as accuracy, consistency, and completeness. The choice of data models, database types, and interoperability frameworks affects how well information can be maintained across systems and over time. At the same time, technological systems are not immune to errors. Issues such as misconfigurations, data loss, and system incompatibilities can introduce inconsistencies or hinder data accessibility. While automation and validation mechanisms can reduce human-induced errors, the effectiveness of these technologies depends on appropriate implementation and governance.

External conditions also influence data quality, as regulatory requirements, industry standards, and evolving business needs define what data must be collected, how it is structured, and how long it remains relevant. Compliance with building regulations, sustainability reporting standards, and data protection laws imposes specific constraints on data handling. Changes over time, such as renovations, regulatory updates, or new measurement technologies, can render previously valid data obsolete, requiring continuous updates and structured version control mechanisms.

### 4.4.2 Measures for data quality management

Managing data quality in BISs is a vast and multi-layered topic, touching on aspects of governance, automation, verification, and compliance. Given its scope, this section does not aim to provide an exhaustive analysis but rather to outline key measures that can actively support data quality management. These measures can be categorized into process-oriented strategies, technological solutions, structured instruments, and actor-related responsibilities, all of which help ensure data remains accurate, complete, and reliable throughout its lifecycle in a BIS.

A key principle is that data quality management is not an isolated task but an integral part of BIS operations. Ensuring high-quality data requires clear process definitions, technological safeguards, structured validation frameworks, and disciplined adherence to standards by actors. Table 4.3 provides an overview of the key categories in data quality management, explaining their role in maintaining high-quality data within BISs.

Table 4.3: Overview on categories of data quality measures for building information systems

| Category | Role in data quality management |
|---|---|
| Processes | Provide the structural and organizational foundation for maintaining data quality by defining responsibilities, governance models, and workflows for error handling and quality assurance. |
| Technology | Serves as both an enabler and a safeguard for data quality, offering automated validation, structured data models, and error detection mechanisms, while also requiring proper implementation and oversight. |
| Instruments | Include standards and certifications that provide formalized frameworks for ensuring that data are collected, stored, and shared in accordance with recognized quality benchmarks. |
| Actors | Responsible for adhering to data quality standards and requirements within BISs, ensuring correct data handling, validation, and continuous improvement through training and accountability mechanisms. |

These categories provide the basis for the following discussion of specific measures and approaches. Although they help structure the analysis, data quality measures often prove to be multi-dimensional, drawing on multiple perspectives simultaneously.

#### 4.4.2.1 Process-Oriented Measures

Process quality plays a crucial role in ensuring data quality, particularly in environments where multiple actors contribute to data collection, storage, sharing, and analysis (Batini et al., 2009, p. 32). Establishing clear data quality requirements from the outset is essential to align all actors within a BIS on expectations for accuracy, completeness, and consistency. This includes defining data governance models that allocate responsibilities for data entry, validation, and maintenance. Additionally, structured workflows for handling errors and inconsistencies ensure that when data quality issues arise, there is a transparent process for resolving them efficiently.

Well-established quality management frameworks, such as ISO 9001 or Plan-Do-Check-Act (PDCA) cycles, provide structured approaches for integrating quality assurance into BIS-related workflows. Certified Quality Management Systems (QMS) offer structured methods for maintaining high-quality data across various domains, reducing the risk of fragmentation and inconsistency (Howarth & Greenwood, 2017, p. 9; Marsden, 2019, p. 82). Process standardization is particularly relevant in phases where large volumes of data are created and exchanged dynamically, such as transactions or renovations.

#### 4.4.2.2 Technological measures

Technological measures support data quality management by automating validation, detecting inconsistencies, and ensuring secure data handling. Some inherent data quality safeguards are tied directly to data models and the way data are structured within BISs. Standardized data models provide predefined constraints that ensure completeness and logical consistency, while metadata-based validation mechanisms help maintain traceability.

Security technologies, which are discussed in detail in section 4.6, contribute to quality management by preventing unauthorized modifications and ensuring data integrity. Beyond security, automated data cleansing techniques help identify and correct errors, whether by detecting missing values, removing duplicates, or normalizing formats (Zwirner, 2021, p. 102). Validation mechanisms embedded in BISs, such as rule-based validation checks or anomaly detection algorithms, can support real-time quality monitoring (Ridzuan & Wan Zainon, 2019, p. 733).

In cases where highly sensitive or critical data are involved, external verification mechanisms offer additional assurance for data quality. Third-party verification, such as independent validation analogous to a notarial role in real estate transactions or the certification of regulatory documentation, helps reinforce trust in shared datasets. Auditing serves as a structured form of such verification, ensuring compliance with contractual or legal requirements. In the real estate industry, this includes external assurance in real estate valuation and due diligence processes, third-party validation of sustainability assessments, or mandatory energy performance benchmarking audits (Cetin, 2024). Similarly, EPCs must be issued by certified professionals and serve as verified summaries of a building's energy efficiency. Complementing these institutional forms of verification, blockchain-based systems can enhance data integrity by ensuring immutability and traceability within decentralized data networks, providing an additional layer of trust and transparency (Treleaven et al., 2021, p. 459) (section 4.6.4).

#### 4.4.2.3 Instrument-based measures

Beyond processes and technologies, structured instruments can help assess and communicate data quality in a transparent manner. Quality labels, such as certifications for data sources or structured data quality indicators, provide actors with aggregated assessments of the reliability and completeness of datasets. Sticking to industry-specific standards offers formalized guidelines for maintaining high-quality data. In the real estate industry, a substantial body of such standards evolved within the last decades. Examples with specifications on data quality include:

- DIN EN 15941:2024-10: *Sustainability of construction works – Data quality for environmental assessment of products and construction works*
- DIN SPEC 91475:2024-03: *ESG – Data Point Initiative for the ecological analysis of Real Estate Stock*
- DIN EN ISO 19650-1: *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)*

Other examples include standardized information sources such as Environmental Product Declarations (EPDs) that ensure that material and environmental data on building products meet predefined quality requirements (DIN EN 15804:2020-03, p. 72). Similarly, green building certifications which serve as quality labels can help reducing the reliance on individual expertise while ensuring that shared data adheres to recognized benchmarks.

#### 4.4.2.4 Actor-based measures

Since actors play a central role in shaping data quality, ensuring disciplined adherence to standards and quality requirements is essential. Even in the presence of well-structured BISs, data quality ultimately depends on how individuals interact with the system, input data, and maintain accuracy over time. This necessitates not only formalized rules and guidelines but also organizational measures that promote accountability and compliance. Examples include regular training programs, internal quality audits, and incentive structures designed to encourage responsible data handling (Khatri & Brown, 2010, p. 152).

The ability to work within standardized data environments, use quality assurance tools effectively, and interpret data correctly influences the overall reliability of BISs. In this regard, suitable access control strategies (section 4.6.1) ensure that data handling responsibilities align with the expertise of different actors, minimizing the risk of unintentional errors or misinterpretations.

## 4.5 Data analytics

The increasing digitization of the built environment is generating large amounts of data across the building life cycle. To derive value from these data, they must be analyzed to generate actionable insights tailored to the specific needs of different actors. ‘Data analytics’ offers tools and techniques to address challenges related to data volume, heterogeneity, and complexity, supporting automation, decision-making, resource optimization, and process efficiency.

This section examines the application of data analytics across the building life cycle, organizing key use cases into development and construction, use, and end-of-life stages (section 4.5.1). The challenges associated with implementing data analytics in BISs are also analyzed (section 4.5.2). Fundamental technologies relevant to data analytics (section C.5.1) and the types of data analytics are introduced in the appendices (section C.5.2). In addition, further evidence regarding use cases of data analytics in the building life cycle can be found in section C.5.3.

## 4.5.1 Use cases throughout the building life cycle

### 4.5.1.1 Development and construction stage

The development and construction stage are highly data-intensive processes where data analytics can significantly enhance planning, decision-making, and execution. These stages often involve large datasets from diverse sources.

For example, during the development stage, project developers require comprehensive datasets to evaluate potential sites and market conditions. Geospatial data from GISs and regulatory data from public records can serve as foundational inputs (Rudolph, 2022, p. 130). The availability of high-quality, up-to-date information enables actors to identify optimal locations with the help of interactive AI-assisted web portals. This reduces manual effort, improves decision-making, and minimizes uncertainty (Nern, 2021).

Data analytics plays a crucial role in optimizing building design by leveraging virtual building models, such as BIM models and digital twins (Bilal et al., 2016, p. 512). These technologies enable simulations that evaluate design options against various criteria, including space utilization, energy efficiency, material efficiency, and structural safety. ML algorithms and advanced simulation tools can analyze data inputs from regulatory requirements, investor preferences, and site conditions to generate and assess design alternatives. For example, deep learning models can suggest layouts or structural configurations that meet specified performance goals, while predictive analytics can estimate how design choices impact life cycle costs and sustainability. By incorporating data analytics into the design process, architects and engineers can create solutions that are better aligned with the needs of investors and other stakeholders, reducing inefficiencies and enhancing decision-making (Baduge et al., 2022, pp. 7–11). In addition, recent developments in generative AI are being explored to support early design phases by producing layout variants or visual materials based on predefined criteria, potentially enhancing ideation and stakeholder communication (Link, 2024).

Energy performance simulations are a key component of AI-supported design processes, allowing for the assessment and optimization of a building's energy demand during the design phase (Bilal et al., 2016, p. 515). Additionally, data analytics can facilitate the automation of calculations required for generating EPCs and other compliance-related documents (Seduikyte et al., 2022, p. 84). Automation also streamlines the creation of reports for investors, stakeholders, or regulatory bodies, supporting tasks such as building permits or compliance checks.

In the construction stage, real-time data collection through IoT devices, wearable sensors, and drones enhances project monitoring and safety management (Baduge et al., 2022, p. 15). For instance, wearable technology provides continuous data on worker activity, environmental conditions, and potential hazards. This information can be fed into predictive models to identify safety risks and optimize resource allocation. Similarly, computer vision applications process image data from drones or site cameras to detect construction progress, compliance issues, or material inefficiencies (Abioye et al., 2021, pp. 7–8).

In addition to enhancing specific tasks, data analytics can play a role in organizing and managing information during the early life cycle stages of development and construction. Given the involvement of numerous actors in construction projects, effective data sharing is essential for ensuring project success. Analytics tools can support the classification and organization of documents, enabling their clear identification through standardized metadata. This streamlines information management, reduces redundancies, and facilitates smoother collaboration across actors (Bilal et al., 2016, pp. 508–510).

#### 4.5.1.2 Use stage

The use stage represents the longest phase in a building's life cycle and offers substantial opportunities for leveraging data analytics to optimize operations, improve efficiency, and enhance sustainability. With continuous data generation from building systems, sensors, and occupant activities, this stage benefits significantly from advanced analytics techniques that enable proactive and data-driven decision-making. The following examples represent only a selection of the potential use cases. A good overview of AI-based data analytics approaches for the use stage can be found in Himeur et al. (2023), for example.

One of the most impactful applications of data analytics in this stage is predictive maintenance. By analyzing monitoring data from building systems and structural components, algorithms can forecast potential failures, allowing structural health monitoring and for timely interventions that minimize disruptions and extend the lifespan of building elements. For example, sensors embedded in HVAC systems or structural materials can continuously collect data on performance, enabling analytics systems to identify anomalies and predict when maintenance is required (Rampini & Cecconi, 2022, p. 898).

Dynamic energy management is another critical application, leveraging data from IoT devices and weather forecasts to optimize energy consumption in real time. Analytics tools can evaluate occupant behavior, building envelope quality, heating system performance, and external conditions to adjust heating, cooling, and lighting systems dynamically, reducing energy waste and improving overall efficiency. These insights not only contribute to operational cost savings but also align with sustainability goals by minimizing GHG emissions (Abioye et al., 2021, p. 8; Pedral Sampaio et al., 2022, p. 15).

In addition to operational benefits, data analytics facilitates the creation of value-added services such as automated post-occupancy evaluations and retrofit planning. Automated post-occupancy evaluations analyze data on building usage and occupant satisfaction to identify areas for improvement, while retrofit planning uses aggregated monitoring data to prioritize energy efficiency measures and coordinate them for maximum impact. Digital twins play a pivotal role in these processes by enabling advanced simulations, including energy performance simulations, to assess the potential impact of various retrofit strategies (Rampini & Cecconi, 2022, p. 896).

Another emerging application of data analytics during the use stage is automated property valuation. By integrating data from building performance monitoring, maintenance records, occupancy patterns, and contextual market information, AVMs can generate up-to-date property value estimates with minimal human input. These models benefit from continuous data flows within BISs, enabling more accurate, transparent, and real-time valuations that reflect both physical and operational characteristics of a building (Su et al., 2021).

#### 4.5.1.3 End-of-life stage

The end-of-life stage, interpreted as the final phase in a building's life cycle without the prospect of redevelopment or reuse, requires careful analysis to address deconstruction or demolition challenges. At this stage, data analytics can provide critical insights for minimizing environmental impacts, optimizing material recovery, and ensuring compliance with regulations.

Key data analytics tasks include:

- Material composition analysis: Evaluating the building's materials to determine which components can be recycled or require disposal, assess the environmental impacts of recycling and disposal processes, and optimize the separation and recovery of valuable materials to support circular economy principles.
- Environmental impact assessment: Using LCA methods and predictive analytics to estimate the environmental impact of demolition activities.
- Compliance and safety monitoring: Ensuring that deconstruction processes adhere to regulatory requirements, such as waste management and hazardous material handling (Baduge et al., 2022, pp. 14–19).

Analytics also assists in planning and optimizing the logistics of deconstruction. For example, predictive models can estimate the volume of waste generated, identify potential recycling facilities, and determine the most efficient transportation routes (Abioye et al., 2021, pp. 7–8). By leveraging historical data from earlier life cycle stages, such as material specifications and construction records, AI-based systems can provide more accurate and actionable recommendations.

The end-of-life stage underscores the importance of maintaining high-quality data throughout the life cycle. Without accurate and comprehensive information on materials, building components, and previous modifications, the potential to apply data analytics effectively diminishes.

### 4.5.2 Implementation challenges

While data analytics offers significant potential throughout the building life cycle, several challenges must be addressed to ensure its effective implementation. A key issue is data quality, especially availability, as many analytics methods require structured, machine-readable, and complete datasets. Unstructured or fragmented data can limit the accuracy of predictive models and reduce the reliability of insights. Additionally, data access is a problem, when restricted due to proprietary ownership or inconsistent standards, making interoperability between different systems difficult (Himeur et al., 2023, pp. 4987–4991).

Another challenge lies in varying levels of actor expertise, use-case specificity, and cultural barriers. Different stakeholders, from large real estate firms to small property owners, exhibit diverse degrees of digital maturity. While advanced AI-driven analytics can yield valuable insights for professional organizations, smaller actors often require simpler and more accessible solutions. To ensure usability and effectiveness, analytical approaches must be tailored to the specific needs and capabilities of each user group. In any case, the demand for AI specialists in the real estate industry is expected to grow further (Abioye et al., 2021, p. 10).

Technological constraints and computing power also play a role. Some analytics applications, such as real-time sensor data processing or AI-based simulations, require high-performance computing and scalable data storage. Not all actors have access to the necessary infrastructure, and solutions must balance computational demands with practical implementation feasibility (Abioye et al., 2021, p. 10).

Financial considerations influence the adoption of data analytics too. Setting up and maintaining analytics solutions can be costly, particularly for smaller firms. These kind of actors must weigh costs and benefits of data analytics technologies carefully (Abioye et al., 2021, p. 10)

Finally, privacy, security, and compliance risks must be considered, particularly for analytics that process sensitive building or occupant data. Regulatory requirements, such as data protection laws, must be met to ensure trust in data-driven decision-making. Additionally, cybersecurity risks increase as more data are collected, shared, and analyzed across multiple platforms (Abioye et al., 2021, p. 10; Himeur et al., 2023, p. 4991).

## 4.6 Data security

Data security is essential in BISs to protect building-related data from unauthorized access, corruption, and loss. Given the multi-actor environment and long-term data use in BISs, security measures must ensure controlled access, data integrity, and resilience across the system's life cycle.

This section examines key aspects of BIS data security: access control mechanisms regulate permissions and secure interactions (section 4.6.1), data ownership and governance define usage rights and responsibilities (section 4.6.2), security measures address preventive and technical protections (section 4.6.3), and blockchain technology explores its role in enhancing data integrity and trust (section 4.6.4).

Further foundational concepts are provided in the appendix:

- Basics of data security (section C.6.1)
- Basics of access control (section C.6.2)
- Data classification and data sensitivity (section C.6.3)
- Threats to data security (section C.6.4)
- Basics of security measures (section C.6.5)
- Basics of blockchain technology (section C.6.6)

While not critical to the analysis of data security in BISs, these aspects offer useful context for a deeper understanding of the topic.

### 4.6.1 Access controlling in information systems

Access control is a fundamental component of data security, ensuring that only authorized individuals can access specific data and resources (section C.6.2). In BISs, where multiple actors might interact with shared data, effective access control is crucial. It safeguards sensitive information, maintains data integrity, and fosters trust by preventing unauthorized access and misuse. Given the diversity of actors and the dynamic nature of building-related data, access control must not only enforce security but also support usability and collaboration. Two options stick out:

- Role-Based Access Control (RBAC) assigns permissions based on predefined roles, making it well-suited for structured, task-oriented environments such as BISs. For example, architects, engineers, or facility managers can be assigned specific access rights based on their responsibilities. However, the static nature of RBAC may pose challenges in dynamic scenarios where access needs frequently change.
- Attribute-Based Access Control (ABAC) provides more flexibility by allowing access decisions to be based on attributes such as project phase, user location, or environmental conditions. This makes it particularly relevant for BISs that integrate real-time data and manage access across multiple life cycle stages.

A hybrid approach combining RBAC and ABAC can offer a balance between structured role-based management and dynamic, context-aware access control. Hu (2018, pp. 47–48) identifies different ways to integrate both models, such as dynamically assigning users to roles based on attributes or refining role-based permissions with policy-based rules. This allows for greater adaptability while maintaining the advantages of predefined roles. Identity and Access Management (IAM) frameworks play a key role in implementing such hybrid models, ensuring that user identities, roles, and policies are managed efficiently while maintaining compliance and scalability in BIS environments.

New developments in access control may further influence future applications. Concepts such as Policy-Based Access Control (PBAC), Risk-Adaptive Access Control (RAdAC), and Self-Sovereign Identity (SSI) introduce more dynamic and decentralized approaches to access management (PricewaterhouseCoopers, 2024). While these trends are gaining traction, RBAC and ABAC remain fundamental for BISs, with hybrid models likely offering the most practical solutions for balancing security, flexibility, and operational efficiency.

### 4.6.2 Data ownership and governance

Data ownership, also called data sovereignty in the context of information systems (Scherenberg et al., 2024, p. 5), generally denotes an actor’s control over data (Graux, 2024, p. 4). The literature distinguishes between ownership and use privileges, whereas use privileges refer to the possibility access, modify, create, and manipulate data while ownership is concerned with the right to control these privileges (Asswad & Marx Gómez, 2021, p. 5). In BISs and similar multi-actor environments typical of the real estate industry, clear ownership frameworks are essential to ensure trust, facilitate collaboration, and prevent disputes over data use. However, defining and managing who can control, access, and use data in BISs is particularly complex due to several factors:

- Overlapping claims on data: Multiple actors contribute to and rely on the same data throughout a building's life cycle, making it difficult to determine exclusive ownership. For instance, as-built documentation may be created by contractors but expected to be controlled by building owners.
- Fragmentation across systems and formats: Data are often stored in different software environments and formats, leading to silos that hinder accessibility and governance.
- Balancing ownership with access needs: While data contributors may claim ownership rights, BISs often rely on shared access to ensure operational efficiency and compliance with legal and contractual obligations.
- Life cycle transitions: Data ownership may shift over time, for example, when a project moves from the construction stage to use, requiring governance mechanisms that reflect these transitions.

To address these challenges, different types of ownership models can be applied. A common distinction is based on how ownership is distributed, differentiating between centralized, decentralized, and federated models. In addition, various data access and compensation models determine how data are shared and monetized (Table 4.4).

Table 4.4: Types of data ownership models and their applicability to BISs based on Mashhadi et al. (2014) and Atlan (2025)

| Type of ownership model | Model specification | Functionality | Applicability to BISs |
|---|---|---|---|
| Distribution of ownership approach | Centralized | One entity holds exclusive control over all data | Simplifies governance and integration; works well in vertically integrated settings but limits actor autonomy |
| | Decentralized | Control over data is distributed among individual actors | Promotes autonomy and flexibility; requires strong identity and access management to coordinate data use |
| | Federated | Multiple actors share control over the same dataset under common rules | Supports collaboration and reduces data duplication; adds complexity to governance and conflict resolution |
| Data access and compensation model | Pay-per-use | Temporary data access priced according to usage | May incentivize sharing in commercial settings; less suitable where trust and transparency are more important |
| | Data market | Data are shared for monetary compensation under specific conditions | Useful for monetizing proprietary data; requires clear contracts and access tracking mechanisms |

| | | | |
|---|---|---|---|
| | Open data | Data are made publicly accessible without direct compensation | Supports transparency and innovation; limited to non-sensitive data and requires proper anonymization practices |

The choice of a suitable data ownership model in BISs depends on various factors, including contractual agreements, regulatory requirements, and the underlying technological infrastructure. One key consideration is the sensitivity or confidentiality of the data involved. Depending on its nature, access to data may be classified as private, restricted, or public, each classification influencing which ownership and sharing models are most appropriate (section C.6.3). Clearly defined access levels help align data use with compliance requirements and actor-specific responsibilities.

ICT plays a crucial role in supporting the practical implementation of data ownership strategies. Technologies such as blockchain (section 4.6.4) facilitate the automation and enforcement of ownership agreements through smart contracts, providing transparency and reducing potential disputes. Metadata and provenance tracking make ownership explicit within data records by documenting origins, changes, and attribution. Access logs further contribute to accountability by recording data interactions. While these technologies do not define ownership per se, they form the technical foundation necessary for operationalizing ownership frameworks.

To integrate data ownership into practice, BISs must be supported by governance frameworks that clarify roles and responsibilities. Assigning data stewards, a role originating in research data management but also extending more broadly to data administration, can help ensure ethical, high-quality, and consistent data use (Wendelborn et al., 2023, p. 4). Formalized data-sharing agreements define ownership, access rights, and obligations among stakeholders (Scherenberg et al., 2024, p. 6). Since ownership structures may shift over time, governance models must remain adaptable to support long-term collaboration, usability, and compliance across all life cycle stages.

### 4.6.3 Measures for data security

Ensuring data security in BISs requires a structured approach that protects shared and sensitive building-related data throughout its life cycle. BISs face specific security challenges, such as securing multi-actor data exchanges, maintaining immutability and traceability of information, and managing security risks in cloud environments.

A key objective of security management in BISs is to minimize unauthorized access, data corruption, and operational disruptions while maintaining accessibility for authorized users. In practice, this requires balancing strong security controls with the flexibility needed for actors to collaborate effectively. Since the characteristics and requirements of BISs can vary, different security measures may be applied depending on the system design and governance framework. The following selection highlights important security aspects relevant to BISs. These aspects should be regarded complementary to basic security measures in information systems as specified in section C.6.5:

- Access control and identity verification help regulate permissions while enabling necessary interactions between different actors across various life cycle stages.
- Ensuring data integrity, immutability, and traceability is essential to maintaining trustworthy information, particularly when data transitions between different life cycle stages.
- Encryption and secure communication protect data from unauthorized access, both during storage and transmission.
- Cloud security strategies include defining governance agreements that address data persistence, encryption policies, and compliance requirements (e.g., service-level agreements). In practice, organizations increasingly evaluate where cloud data are physically stored, as data location can be a factor in legal compliance and trust (e.g., preference for servers within specific jurisdictions).

Security considerations are particularly relevant when dealing with multi-actor access to critical building information. The transition of data across lifecycle stages, such as from construction to operation, introduces risks related to data integrity, versioning, and access governance. Clear access policies and protection mechanisms help mitigate these risks while maintaining data usability.

As cloud-based BISs and platforms become more common, security strategies must ensure data sovereignty and compliance with regulations. Organizations using cloud services must consider jurisdictional requirements, contractual safeguards, and data protection standards to ensure long-term data security and reliability.

By implementing security measures that address these BIS-specific risks, organizations can strengthen trust among actors and ensure that BISs function as a secure and reliable single source of truth for building-related information.

## 4.6.4 Blockchain technology

### 4.6.4.1 Blockchain use cases

Blockchain technology has gained increasing attention within the real estate industry due to its potential for ensuring data integrity, traceability, and decentralized trust mechanisms. While primarily known for its role in cryptocurrencies, blockchain offers data security and governance features that are also relevant for BISs. Blockchain's key characteristics, including immutability, decentralization, and cryptographic security, enable new approaches to data storage, verification, and collaboration (section C.6.6).

In the context of BISs, blockchain does not replace existing data infrastructures but rather has the ability to serve as a complementary mechanism to enhance trust, security, and transparency in multi-actor data environments. Depending on the life cycle stage, blockchain can support various BIS applications, as summarized in Table 4.5.

Table 4.5: Use cases of blockchain in the real estate industry

| Life cycle stage | Possible applications of blockchain | Evidence |
|---|---|---|
| Development stage | Land administration and registration | (Mezquita et al., 2022, p. 1019; Saari et al., 2022, p. 7) |
| Construction stage | Traceability in supply chain management | (Eckert, 2018, p. 827) |
| | Replacing centralized confidentiality authorities (notary) | (Eckert, 2018, p. 827; Saari et al., 2022, p. 10) |
| | Smart contracts | (Saari et al., 2022, p. 10) |
| | Assignment of unique object identifiers (UBIs) for building components and buildings | (Jedelsky, 2022, p. 480) |
| | Storing of BIM projects | (Ganter & Lützkendorf, 2019, p. 6; Turk & Klinc, 2017, p. 643) |
| Use stage | Traceability of owner history | (Eckert, 2018, p. 827) |
| | Protocolling of real estate management and maintenance activities | (Saari et al., 2022, p. 12) |
| | Replacing central administration in IoT networks | (Eckert, 2018, p. 827) |
| | Real estate tokenization | (Jedelsky, 2022, p. 479; Saari et al., 2022, p. 9) |
| | Integration with digital twins | (Hellenborn et al., 2024, p. 25; Tavakoli et al., 2024, p. 6) |
| End-of-life stage | Traceability of construction materials and products | (Celik et al., 2023, p. 13) |

A widely discussed application of blockchain is the use of smart contracts. Unlike traditional contracts, smart contracts operate as self-executing digital agreements stored on a blockchain, automating processes such as service-level agreements (SLAs), payments, or access control enforcement (Eckert, 2018, p. 836). For BISs, this could streamline transactions between actors while reducing administrative overhead and increasing compliance transparency.

Beyond security applications, blockchain is also considered for long-term data storage and archiving in BISs. As building-related data accumulates over decades, ensuring its verifiability and immutability becomes a challenge. Blockchain could serve as a tamper-proof registry for key building information, including planning records, building permits, and ownership history.

#### 4.6.4.2 Implementation challenges

While blockchain presents significant opportunities for BISs, its implementation must be carefully managed to address technical, organizational, and regulatory challenges. A major consideration is balancing transparency with data confidentiality. Since blockchain inherently preserves all transactions in a distributed ledger, integrating it with privacy-enhancing techniques, such as encryption and permissioned blockchains, is necessary to protect sensitive building-related data (Garcia-Teruel, 2020, p. 141; Hunhevicz & Hall, 2020, p. 9).

Another challenge is scalability, particularly for high-volume data such as real-time data from technical monitoring. While blockchain ensures data integrity, its efficiency decreases as the size and frequency of recorded transactions increase (Garcia-Teruel, 2020, p. 136). This highlights the need for hybrid approaches, where blockchain is selectively applied for critical records, such as data with a high level of sensitivity, rather than general-purpose data storage (Parn & Edwards, 2019, p. 259). Moreover, the benefits of automation, immutability, and traceability, often associated with blockchain, should be evaluated carefully, as many of these advantages can also be achieved through broader digitalization strategies without introducing blockchain-specific complexity.

From a legal and regulatory perspective, the decentralized nature of blockchain also raises data sovereignty concerns. In practice, organizations increasingly scrutinize where data are physically stored, even when using decentralized networks. In cloud-based BISs, this issue is already a concern, as certain regulations (e.g., GDPR) require data to be stored within specific jurisdictions. Blockchain implementations must therefore align with governance frameworks that clarify data residency, access rights, and compliance measures (Hunhevicz & Hall, 2020, p. 9).

Additional legal challenges include the reliable identification of involved parties, the legal validity and enforceability of smart contracts, and the verification and protection of property rights that are directly attached to the asset itself. Furthermore, practical issues such as registering co-ownership, making legally recognized amendments to an immutable ledger, and ensuring consumer protection remain unresolved in many jurisdictions (Garcia-Teruel, 2020, p. 136).

Although blockchain is often associated with disintermediation, in practice, the removal of intermediaries in BISs may not always be feasible or desirable. Trusted third parties, such as regulators, certifiers, or data verifiers, may still play a critical role, particularly in contexts requiring legal accountability, data validation, or complex stakeholder coordination. This reflects findings in other domains, where disintermediation has remained limited despite technical possibilities (Saari et al., 2022, p. 16).

Furthermore, the successful application of blockchain in BISs depends not only on technical architecture but also on organizational readiness. Barriers such as limited technical expertise, resistance to change, and misalignment between stakeholders can significantly delay or hinder adoption. These challenges underscore the need for targeted capacity building and clear incentives, especially in sectors where traditional data practices remain dominant (Saari et al., 2022, p. 13).

While blockchain is not a universal solution, it introduces new possibilities for enhancing security, transparency, and long-term data reliability in BISs. Its success, however, depends on careful integration with BIS architectures, a realistic assessment of its added value, and the ability to address both technical and institutional challenges in practice. Given its storage limitations and associated costs (Hunhevicz & Hall, 2020, p. 9), blockchain is unlikely to serve as the primary data storage medium in BISs. Instead, it is better suited as an additional verification layer, integrated with cloud platforms or federated data infrastructures to ensure data integrity and trustworthiness.

## 4.7 Summary

This chapter analyzed the role of ICT in building-related information management, focusing on its implications for data collection, storage, sharing, quality management, analytics, and security. The findings highlight critical challenges and requirements for BISs, particularly in ensuring structured, interoperable, and scalable information management across diverse actors and life cycle stages.

- **Data collection** requires integrating structured and machine-readable data into BISs while ensuring interoperability with later processes. Original data collection techniques often demand experts and specialized systems, making data transfer and standardization crucial for BIS usability. The smooth integration of primary and secondary data sources emphasizes the need for interoperable formats, efficient workflows, and structured data models.
- **Data storage** must be modular and adaptable to different data types, supporting flexible combinations of cloud and local storage depending on security and control requirements. Multi-actor environments benefit from cloud-based solutions, while large enterprises or highly sensitive data may require hybrid approaches. Architectural patterns that ensure scalability, flexibility, and structured data organization are essential.
- **Data sharing** remains a challenge due to the coexistence of structured and unstructured formats. While structured data enables interoperability and further processing, many actors still rely on semi-structured or unstructured formats. LD/SW technologies offer potential for bridging data standards, though existing building-related standards are often too complex or rigid for widespread adoption. The increasing trend of platforms and data rooms integrates multiple technologies to enhance data sharing between actors.
- **Data quality management** is not an isolated task but must be integrated across all stages of information management. Quality is influenced by multiple factors, requiring defined requirements for different data types and appropriate automated validation and structuring measures. Ensuring traceability, reliability, and compliance with data governance frameworks is key to maintaining high-quality datasets.
- **Data analytics** offers considerable potential throughout the entire building life cycle, from design optimization to predictive maintenance and sustainability assessments. However, data quality and structure significantly impact the feasibility and effectiveness of analytics applications. Tailored solutions are necessary, aligning analytical methods with the specific characteristics of available data and the needs of actors.
- **Data security** is a fundamental aspect of information quality and includes access control, data ownership and management, dedicated security measures, and the potential application of blockchain technology. In multi-actor environments, security mechanisms are essential for creating trust and ensuring compliance, balancing openness with protection of sensitive information.

The chapter underscores that BISs must integrate ICT solutions tailored to information management tasks while prioritizing interoperability, flexibility, and security. These findings provide the foundation for defining a requirement profile in the following chapter, ensuring that BISs are designed to meet practical challenges and emerging demands in the digital management of building-related data.

# 5 Development of a requirement profile for a life cycle building information system

*There are permanent difficulties in dealing with building-related data and unresolved matters in life cycle-oriented information management. At the same time, modern technologies offer significant potential for enhancing building-related information management. The question remains how the knowledge about data requirements and about technical solutions can be used in a BIS that assists building owners and other actors throughout the life cycle. To answer this question, chapter 5 builds upon the insights of chapters 2, 3, and 4 in order to formulate requirements that a BIS should fulfill ideally. This approach to systematically deriving a requirement profile for a BIS based on both theoretical and practical insights does not yet exist in this form in the literature.*

*First, the role of BISs will be grounded in information management and the initial definition will be enhanced to indicate the life cycle perspective (section 5.1). Second, general requirements on the main functions, system boundaries and usefulness (section 5.2) as well as actor-specific requirements will be formulated (section 5.3). Third, requirements on the availability (section 5.4) and overall quality of building-related data in a BIS (section 5.5) will be identified, before also system-related requirements will be dealt with (section 5.6).*

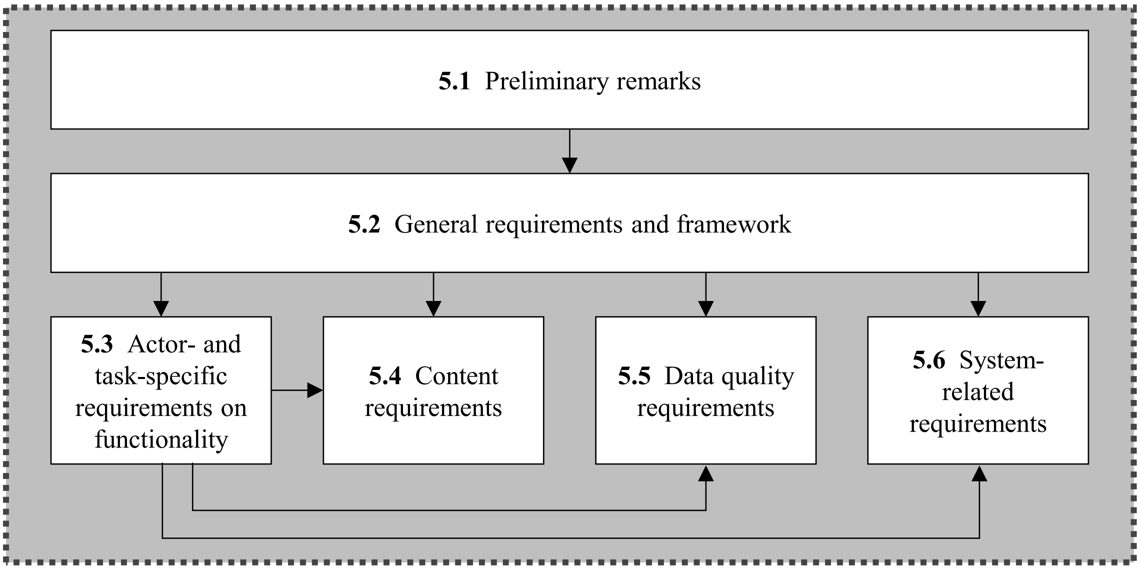



Figure 5.1: Structure of chapter 5

## 5.1 Preliminary remarks

Before specifying concrete requirements, it is necessary to clarify the role of BISs in the broader context of building-related information management. Section 5.1 outlines how BISs are connected to fundamental information management tasks and identifies the core processes they are intended to support. In doing so, it establishes the conceptual foundation for deriving requirements, which will be further specified and extended with a life cycle perspective in the subsequent sections.

### 5.1.1 Building information systems and information management tasks

BISs are expected to facilitate improvements in building-related information management. Actors that are involved in the design, construction, and operation of a building are in need of specific solutions for information management. This specificity is based on tasks that actors fulfill on specific occasions in the building life cycle. A BIS should ideally offer an appropriate information management solution for a specific task and therefore meet the demand of actors on those solutions. This connection has been specified in a former publication from the author (Figure 5.2).

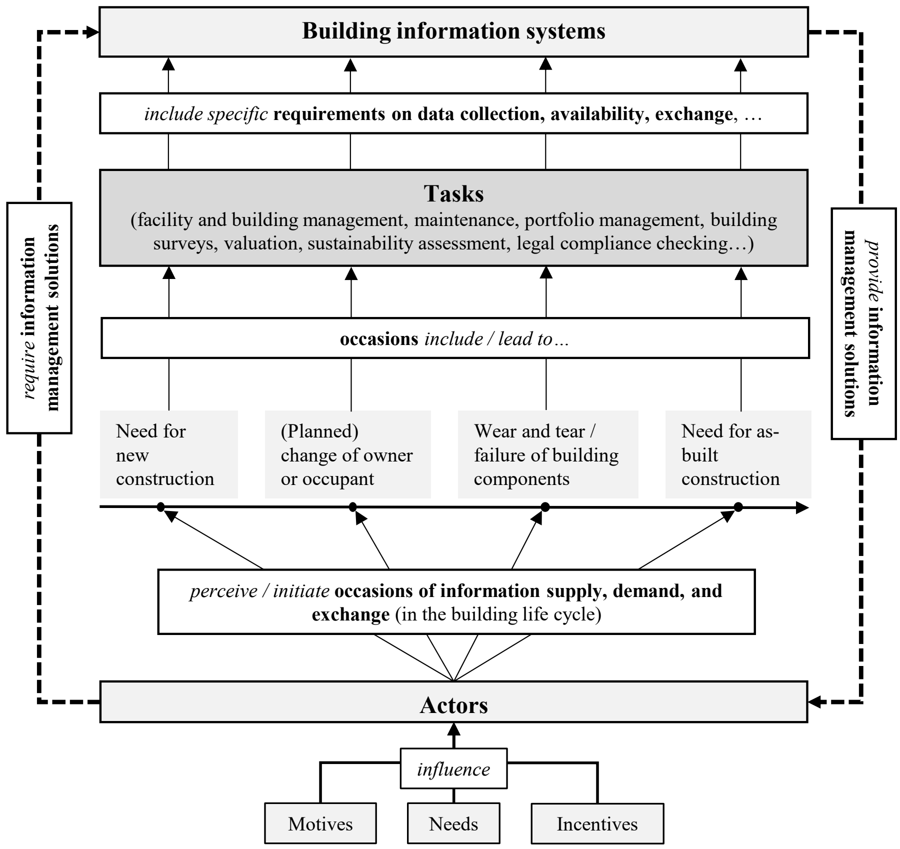



Figure 5.2: Role of building information systems in the context of life cycle information management (Buchholz & Lützkendorf, 2024, p. 3)

According to its definition (section 2.2.5), information management refers to the management of the supply, demand, and exchange of information. A main requirement on BISs is therefore to bridge the existing gap between information supply and demand in tasks during the life cycle of a building. Traditionally, this gap can be large in the real estate industry compared to other industries, based on diverse problems in information management (section 3.4). Based on the basic functions of information management (Krcmar, 2015, p. 118), a BIS should assist the management of…

- information sources, such as the object of consideration (e.g. a building),
- information resources, acting as the representation of information within the system,
- information supply, facilitated by an application software with which users use the system,
- information needs and demand of potential users,
- information usage, depending on the scope of use cases, and
- information processing and communication in order to facilitate the information flows.

These dimensions represent the core of a holistic approach on information management (section 2.2.5). In order to achieve the intended relevance in building-related information management in a modern ICT environment, a BIS must facilitate the core processes of dealing with building-related data: Collecting, storing, and sharing. Within the following sections, the specification of a requirement profile will identify the preconditions for a BIS to meet these functions.

### 5.1.2 Need for a life cycle building information system

The findings of the analysis in chapter 3 concerning information management within the real estate industry included two main aspects: First, the long-term storage and maintenance of building-related data is crucial to make these data available in the right quality when needed at specific occasions. Second, this need for data results in the need to create and collect a specific set of data throughout several life cycle stages.

With the help of these aspects, the role of BISs can be concretized. By enhancing the initial definition of a BIS (section 2.4.1), the need for improvements in building-related information management can be addressed. The crucial aspect lies in adding the life cycle perspective to the definition in order to stress the need for an overarching connection and interoperability between building-related data, tasks, actors, tools, and technologies. Additions are indicated in bold.

*A **life cycle** building information system (**LC**-BIS) is a human-machine-interrelated system that supports building owners and other actors involved in managing building-related information **throughout the building life cycle** by facilitating the collection, storage, sharing, and use of building-related data.*

The overriding goal of such a system is to support real estate management through improved information management. On the level of individual buildings, this includes pursuing sustainability-related objectives such as limiting environmental and climate-related impacts or preserving the asset value over time. These effects become even more pronounced when LC-BISs are applied at the level of building portfolios or entire building stocks. In this broader context, LC-BISs can contribute to higher-level management decisions by enabling transparency, reducing information gaps and asymmetries, and thereby supporting a long-standing goal within the real estate industry.

The following sections will specify requirements that should be met by a LC-BIS in order to match its definition.

## 5.2 General requirements and framework

Section 5.2 outlines the overarching requirements that define the scope and functional orientation of LC-BISs. These include requirements regarding the object of consideration (section 5.2.1), the main system functions (section 5.2.2), and the expected usefulness and economic viability of the system (section 5.2.3). Together, these aspects form the framework conditions under which LC-BISs can support life cycle-oriented information management.

### 5.2.1 Requirements on objects of consideration

A LC-BIS should primarily focus on *individual buildings* and their inherent characteristics. This includes the properties and attributes of a specific building, framed as "building-related data", as defined in section 3.1.1. The scope of building-related data maintained in a LC-BIS should be clearly defined in order to specify its functionality and separate it from other BISs (section 5.4 Content requirements).

A LC-BIS is not necessarily confined to particular building use types, but should be applicable to both *residential and non-residential buildings*. Variations in data scope and quality, notably in terms of granularity, may arise between smaller and larger structures or across diverse applications. Recognizing these differences is essential to ensure that the LC-BIS remains adaptable to diverse building contexts while meeting its intended requirements.

In the case of buildings with multiple owners, such as condominiums, cooperatives, or mixed-use properties, the object of consideration within a LC-BIS must be clearly delineated. While the system may focus on the building as a whole, it must also account for the partitioning of ownership, which affects both the scope of data included and the allocation of responsibilities. Data related to shared infrastructure (e.g., roofs, elevators, heating systems) should be distinguished from data specific to privately owned units. This differentiation is essential for assigning access rights, ensuring data privacy, and supporting relevant decision-making processes for both individual owners and collective governance structures.

A defining requirement for a LC-BIS is its integration of a *life cycle perspective*, extending its applicability across all stages of a building's existence. These stages span from initial planning and design through construction, operation, renovation, and ultimately deconstruction or demolition (section 2.1.3). This comprehensive viewpoint should enable the LC-BIS to manage and disseminate data that remain pertinent and actionable throughout the building's life cycle, addressing the evolving needs of actors.

To support life cycle management effectively, a LC-BIS must classify building-related data against time. This includes:

- Documenting the creation or collection timeline of data.
- Determining the validity period of data relative to specific life cycle contexts or stages.
- Tracking version histories and changes over time, particularly for tasks such as building permitting, renovation planning, and updates.

Temporal considerations ensure that data remain reliable, current, and relevant for decision-making processes throughout the building life cycle.

The scope of a LC-BIS addresses a *wide range of actors and their tasks* throughout the building life cycle. Actors include the owners of building-related data, as well as those who create, demand, or utilize such data. These could include, for example, building owners, professionals in the construction industry, real estate managers, and regulatory bodies. The LC-BIS should be useful to time-specific tasks such as building permits, object documentation, handovers, maintenance, refurbishments, and general real estate management, including portfolio, asset, and facility management. Additionally, it should accommodate functional tasks that occur at multiple life cycle stages, such as property valuation, risk management, marketing, and sustainability assessments and reporting.

### 5.2.2 Requirements on core functions

The following core functions result from the overarching purpose of supporting information management in the broader sense and data management in the narrower sense. To establish LC-BISs as effective tools for life cycle-oriented information management, several key roles can be identified. The primary role is that of a data storage system, or *data repository*. In this role, a LC-BIS should be able to provide building-related data needed for actors and their tasks. Actors must be able to access data from a LC-BIS when required. It should serve as an interoperable tool that integrates building-related data from diverse sources, functioning as a single source of truth to enhance data reliability and trust among actors.

Moreover, based on its life cycle orientation, the LC-BIS should enable consistent data collection and storage ("*durchgängige Datenhaltung"*) across all life cycle stages. This is crucial to minimize media discontinuities and information loss, which are particularly common at life cycle transitions or during handovers between actors. In addition, the LC-BIS should organize data in a way that makes transactions with the data repository effective and efficient. This organization, potentially supported by a data model and ICT infrastructure, contributes to managing data quality. Even if not defined as a dedicated *data quality management tool*, a LC-BIS can make a substantial contribution in this regard.

Another requirement on the main functions of a LC-BIS is that it enables a structured and standardized process of "writing" data on the data repository. In this way, it can also take in a role as a *documentation tool*, that supports the systematic collection of building-related data at specific occasions throughout the building life cycle, such as construction documentations, maintenance activities, or transactions. Realizing the potential benefits of this role depends on ensuring that critical data are systematically integrated into the LC-BIS, addressing the information needs of actors effectively.

Additional to adding and reading/retrieving data, LC-BISs should enable the alteration and updating of selected data on the repository. By fulfilling these three main functions, LC-BISs can substantially contribute to managing the supply, demand, sources, and resources of information (section 5.1.1).

By meeting the functions as a data repository, LC-BISs facilitate data sharing among actors. In order to work as a comprehensive tool for information management, LC-BISs should ideally cover real-time communication between different actors too. In this sense, LC-BISs should act and be interpreted as *communication platform*. Real-time communication can foster enhanced collaboration, reduce delays in decision-making, and support the synchronous exchange of building-related information across actors.

Table 5.1 gives an overview of the interpretation of the roles a LC-BIS fulfills.

Table 5.1: Core functions and characters of life cycle building information systems

| Interpretation as… | Explanation |
|---|---|
| Data repository (data and document collection) | Life cycle-oriented collection of building-related data and documents with the goal to store and manage information and make it available when needed |
| Documentation tool | Tool that facilitates the systematic collection of building-related data either for a specific task in the building life cycle or across different activities |
| Data sharing / Communication platform | Collaborative platform that enables options for communications for different actors throughout the real estate value chain |
| Data quality management tool | Tool to ensure the right quality of building-related data according to the preferences of users by facilitating data organization and implementing processes to meet data quality goals |
| Standardization tool | Tool for a standardization of building-related data in terms of data formats, data structure, and information management processes in general |
| Digitalization tool | Tool that enables actors of the real estate industry to digitize building-related data and processes by taking advantage of suitable ICT solutions |

By taking in these roles, a LC-BIS can substantially contribute to support decision-making, administration, and knowledge management for building-related tasks. Beyond the core roles, LC-BISs can evolve to fulfill additional roles and provide extended functions, such as:

- *Data analytics and assessment tool*: Automated processes to analyze data that are available in a LC-BIS, e.g. for sustainability assessments, property valuations, risk assessments etc.
- *Action plan and guide*: Active decision support based on prescriptive data analytics, e.g. for decarbonization roadmaps or predictive maintenance

- *Visualization tool*: Visualization of data to improve comprehensibility, also in connection with virtual building models (BIM, digital twins)
- *Data and document creation tool*: Creation of new data through data analytics and automated processes and structurization in specific documents, e.g. for sustainability reporting

Figure 5.3 shows in a simple scheme how the functions can be understood in the overall context of the BIS functionality. The data repository function is central to facilitate other functions.

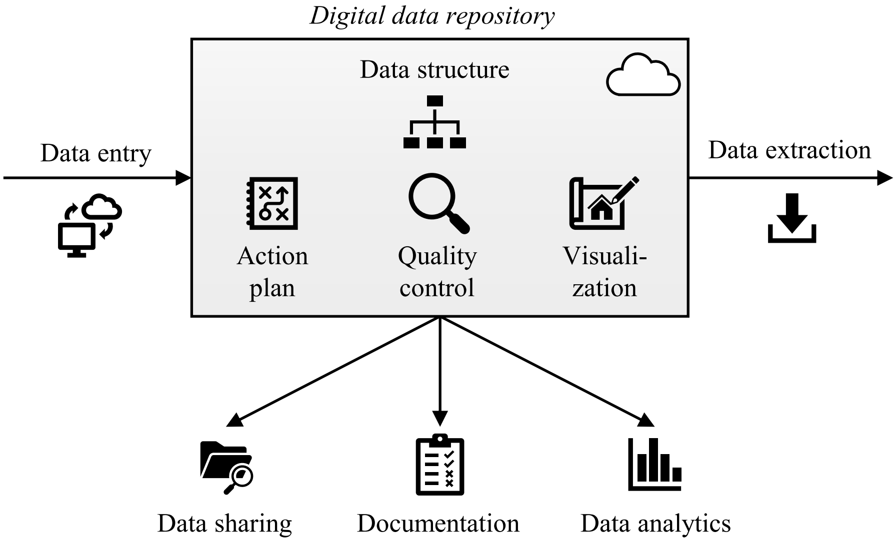



Figure 5.3: Core functions and extended function of life cycle building information systems

The functions described in this section will be considered in the specification of actor-specific requirements (section 5.3) and in the analysis of existing BISs (chapter 6).

### 5.2.3 Requirements on usefulness and economic viability

A LC-BIS must be economically viable or, at the very least, advantageous in a broader sense, ensuring that its benefits outweigh its costs over the longer term. *Economic viability* is expected to be a fundamental condition for the successful implementation and sustained use of LC-BISs, a point also highlighted by expert input (section B.1).

The overarching hypothesis is that life cycle-oriented information management, supported by LC-BISs, holds significant potential for the real estate industry. However, a key challenge lies in determining whether actors in the industry can adequately value building-related data and whether the value of such data can be appropriately monetized. This underscores the need for LC-BISs to demonstrate clear, quantifiable benefits to encourage adoption and investment.

Two typical challenges of information management in the real estate industry must be addressed to achieve economic viability:

1. Short-Term Costs vs. Long-Term Benefits: There is a prevailing tendency within the industry to prioritize the short-term costs of information management, particularly data collection, over the long-term benefits derived from structured, life cycle-oriented data use. This mindset often inhibits the realization of the full value potential of LC-BISs.
2. Uneven Distribution of Costs and Benefits: The costs and benefits associated with data management are often distributed unevenly among actors. For example, data required during the use stage must frequently be collected during construction or final inspection. Yet, construction companies are typically not commissioned to perform this task and lack inherent motivation to do so, as they do not directly benefit from these data during their immediate scope of work.

These challenges not only affect actors in their different roles across the building life cycle but also impact individual employees within organizations, who may struggle to justify the allocation of resources toward long-term data initiatives.

To ensure economic viability, solutions are needed to address the systemic challenges outlined above. These solutions should include the development of business models and contractual arrangements that:

- Align incentives across different actors and life cycle stages, ensuring that those responsible for data collection are appropriately compensated or motivated.
- Promote shared value creation by demonstrating how LC-BISs generate tangible benefits for all involved actors over the life cycle of a building.
- Support mechanisms to quantify and communicate the value of high-quality building-related data.

On the other hand, the costs associated with the initial setup, administration, and use of a LC-BIS should remain at a manageable level, as excessive costs may deter potential users. This consideration extends beyond monetary expenses to include factors such as the skills required to operate the system. This aspect is closely linked to the requirements for ease of use and operability of a BIS (section 5.6).

Another key requirement for LC-BISs is to mitigate risks associated with incomplete or poor-quality data. In a fast-paced economy, where decision timelines are shrinking, actors in the real estate industry are beginning to recognize the risks of inadequate data management. This recognition is partly driven by external pressures, such as non-financial reporting obligations, but there remains substantial potential for further integration of data as a central component of risk management strategies. By addressing these risks, LC-BISs can influence the economic assessment of data collection and storage, emphasizing their role in reducing uncertainties and fostering value creation.

# 5.3 Actor- and task-specific requirements on functionality

Section 5.3 focuses on how LC-BISs must accommodate the diverse needs of actors and tasks throughout the building life cycle. Building on the general system requirements, the section differentiates between requirements arising from core life cycle tasks (section 5.3.1), cross-functional tasks (section 5.3.2), the public sector (section 5.3.3), and sustainability-related activities (section 5.3.4). The goal is to ensure that LC-BISs provide targeted support for specific decision-making contexts

## 5.3.1 Tasks throughout the life cycle

LC-BISs should support actors throughout the building life cycle, aligning with the core tasks of each stage. Their functions must adapt to different life cycle requirements to ensure efficient information management, data accessibility, and decision support.

In the early life cycle stages, information management is characterized by intensive data creation and the need to document information for later use. However, data collection is often perceived as an additional burden in construction projects. To address this, LC-BISs need to streamline data collection and documentation by setting out clear instructions on required data formats and quality standards, reducing redundant workloads and ensuring standardized handovers. This requirement is closely linked to the system's usefulness and economic viability. Additionally, interoperability with data sharing and storage solutions is crucial. Depending on the specific use of BISs in a project, a LC-BIS must integrate with data from BIM applications, project management tools, and other systems to avoid inefficiencies. Throughout these processes, the system should contribute to maintaining data quality, ensuring completeness, consistency, and compliance with standards.

Once the building is in use, the need for structured information access, data sharing, and decision support becomes particularly relevant (Figure 5.4). Industry experts highlighted standardized object documentation as a key foundation for providing targeted support and actionable recommendations (section B.2). Two of the most frequently mentioned tasks that benefit from LC-BIS functions are the planning of small- and large-scale renovations and the long-term monitoring of building performance, including energy performance. Depending on their role, actors have different expectations of the system: portfolio managers, asset managers, and facility managers require task-specific solutions for managing and accessing building-related data, often leveraging advanced functions such as data analytics, visualization, and automation. Smaller organizations or individual users may prioritize ease of use and intuitive system navigation. The requirements also depend on building-specific factors such as type, size, and complexity, which influence the necessary level of detail and system functionalities. A crucial aspect is interoperability with other BISs, ensuring smooth integration across different workflows and enabling data-driven decision-making.

At later stages of the life cycle, the LC-BIS must ensure that relevant information remains accessible and comprehensible. This is particularly important for deconstruction planning and execution, where reliable documentation supports material recovery, compliance with sustainability objectives, and optimized decision-making.

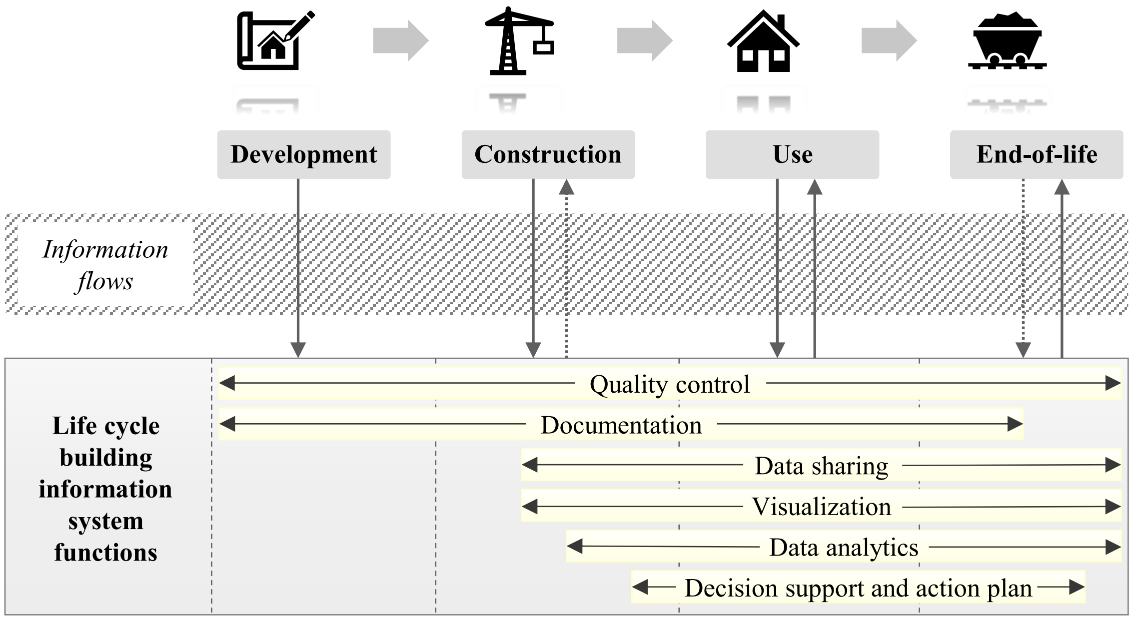



Figure 5.4: Relevance of life cycle building information systems functions throughout the building life cycle

## 5.3.2 Cross-functional tasks

Cross-functional tasks, often carried out by experts such as building surveyors, risk analysts, and marketing professionals, pose specific requirements on LC-BISs. These tasks benefit from the system's core functions, particularly as a data repository and communication platform, enabling centralized access to high-quality building-related data.

For property valuation, a LC-BIS must support the provision of building-related data in the appropriate quantity and quality. Ideally, surveyors can access data that are increasingly relevant in property valuation, particularly in the context of sustainability criteria. Based on the availability of high-quality building-related data, LC-BISs offer potential for automation to streamline valuation processes, either by reducing manual data input or by facilitating algorithm-based assessments. These requirements reflect the potential for LC-BISs to broaden access to valuation insights for both experts and non-experts.

In risk management, actors rely on building-related data to assess performance and location-specific risks. Standardized and readily available data are essential to support consistent and reliable risk assessments. In property transactions, LC-BISs can reduce the costs and efforts associated with due diligence, enabling more efficient and timely decision-making.

For marketing, LC-BISs can serve as the foundation for automated processes such as generating real estate brochures and integrating virtual reality technologies to enhance presentation capabilities. Requirements include the ability to structure and access data efficiently, reducing manual effort and costs while improving marketing outreach. Moreover, LC-BISs that facilitate data sharing and communication between actors and building owners enhance collaboration in cross-functional workflows, improving efficiency and reducing inconsistencies.

### 5.3.3 Public sector perspective

The public sector, in its roles as building owner, developer, legislator, and policymaker, places specific requirements on LC-BISs to support its diverse responsibilities. Public authorities often depend on reliable and comprehensive data for strategic decision-making, urban planning, and the monitoring of national building stocks. These requirements include access to basic building-related data for generating statistics on aspects such as building use types, energy performance, and housing availability. LC-BISs can provide such data, helping to reduce costs associated with manual surveys and fragmented data collection efforts. The insights gained can feed into the (further) development of national building registers. At the European level, this could support the EU's efforts to digitize public service administration, for instance within the framework of the "New European Interoperability Framework" (European Commission, 2017)

Building authorities specifically require LC-BISs to facilitate the digitalization and standardization of administrative processes, such as building permits, compliance monitoring, and legal certifications. A widely adopted and trusted LC-BIS can improve workflow efficiency, transparency, and communication between public bodies and private actors. LC-BISs could also facilitate digital building permitting, improving efficiency and reducing administrative burdens.

### 5.3.4 Sustainability assessments and reporting

Sustainability assessments and reporting tasks require LC-BISs to address challenges such as fragmented data quality and insufficient standardization. A key requirement is ensuring both the provision of building-related data for assessments, including master, inventory, economic, and performance data, as well as the infrastructure to store and share assessment results. For comprehensive sustainability assessments with a specified structure, contextual information and results can be stored within a dedicated sustainability assessment log, while specific data points can also be integrated more granularly depending on the requirements of a given data model.

Ensuring that sustainability assessment results remain accessible for other life cycle tasks, such as facility management, property valuation, and risk management, is essential. Automation of sustainability-related tasks, such as energy consumption tracking, waste reduction monitoring, and LCAs, represents a potential future development for LC-BISs, leveraging their role as foundational platforms for managing and integrating relevant data.

Industry experts also view real-time reporting as a potential future capability of LC-BISs, relying on their ability to provide high-quality data for sustainability management (section B.1). By offering a structured and reliable basis for integrating sustainability metrics into life cycle decision-making, LC-BISs can support the evolving needs of real estate companies and their long-term environmental objectives.

## 5.4 Content requirements

Building-related data lie at the heart of a LC-BIS, forming the foundation for fulfilling its functions and addressing actor- and task-specific requirements. Analyzing the needs for building-related data across the various tasks and stages of the building life cycle is essential for defining the requirements on data content.

This section begins by explaining the relevance of different data types, including the significance of data categories, quality characteristics, documents, linked data, and metadata. Following this, an overview of the required data points is presented based on an intuitive classification. While detailed lists of data points are provided in the appendix, the main focus here is on discussing why certain types of data are necessary and how they contribute to the overall data content framework.

### 5.4.1 Relevance of data types

#### 5.4.1.1 Raw data categories

As defined in section 3.1.2, raw building-related data refer to unaltered data that are created or collected in relation to a specific building. These categories help shape the definition of building-related data and serve as a foundation for life cycle-oriented information management. To effectively support actors and ensure applicability across various use cases, a LC-BIS must encompass all categories of raw building-related data. This inclusivity prevents data from being structured solely around individual actor requirements, thereby enhancing interoperability and reusability.

For better clarity and usability, it is beneficial to consolidate these categories into four essential and logically distinct groups, as applied in the taxonomy of data needs throughout the life cycle (section 3.3.8.2). Table 5.2 outlines the rationale for integrating these categories within a LC-BIS, emphasizing their importance for comprehensive information management.

Table 5.2: Relevance of raw data categories in a life cycle building information system

| Data category | Relevance in LC-BISs |
|---|---|
| Master data | Crucial for tasks across the building life cycle, providing fundamental identifiers to ensure clear object definition and consistent referencing across systems. |
| Inventory data | Represent the physical structure and technical characteristics of a building. Essential for most life cycle decisions, particularly in construction, modernization, and maintenance. |
| Economic and legal data | Essential for strategic and financial decisions. Legal data define key constraints and compliance requirements across multiple tasks. |
| Performance data | Typically dynamic, enabling the tracking of building performance over time and supporting data-driven decision-making. |

#### 5.4.1.2 Processed data

Building-related decisions throughout the life cycle are often complex and require significant data support to ensure optimal outcomes. With increasing demands for sustainability, efficiency, and compliance, the role of actionable and easy-to-interpret indicators has become particularly important. These indicators, such as metrics for global warming potential, financial performance, and value enhancement potential, help condense data into usable insights, supporting actors across various roles. Asset managers, for example, rely on such indicators to assess technical and environmental quality.

These indicators can originate from external information sources or documents, such as EPCs, or be derived from raw data within the LC-BIS itself. This underscores the critical link between raw and processed data, as raw data serve as the foundation for analysis, assessments, and decision support. Without reliable raw data, meaningful processing and interpretation would not be possible.

Beyond indicators, processed data also include outputs from data analytics functions, such as proposals for actions or complete action plans. These extend to nearly all strategic and operational management tasks within a building's life cycle. Examples include:

- Asset strategy recommendations, aiding long-term portfolio and investment decisions.
- Guidance and support in building management, optimizing operational efficiency and resource use, for example through alerts or maintenance proposals.
- Renovation roadmaps, providing structured proposals to improve energy performance and reduce emissions.

The specific data points resulting from data analytics functions depend on the scope to which these functions are implemented. By integrating raw and processed data, a LC-BIS could enable advanced decision-making, automation, and efficiency gains across all life cycle stages.

#### 5.4.1.3 Documents and files

Documents and files have long been a cornerstone of information management in the real estate industry. Historically, the industry has relied on hardcopy documents to store and exchange information. While technological advancements have facilitated the digitization of these documents, many actors still rely on unstructured or semi-structured formats, such as PDFs, scanned images, or Word files. At the same time, modern information systems are increasingly focused on fine-grained data stored in structured formats.

To accommodate diverse user needs, a LC-BIS must support both granular data and document-based information. Non-expert users may prefer document-based formats for accessibility, while professionals require structured data points for advanced analysis and automation. This requires mechanisms to ensure consistency between data stored as discrete entries and data embedded within documents, enabling:

- Generate documents from individual data points (e.g., assembling a maintenance manual from stored maintenance logs).

- Extract relevant data points from existing documents (e.g., parsing energy performance data from an EPC).
- Maintain consistency across formats, ensuring that updates to raw data are reflected in associated documents and vice versa.

Documents are generated and used throughout the entire building life cycle. Their importance spans a wide range of functions, from facilitating production and service documentation to serving as comprehensive information containers during data exchange. Table 5.3 highlights examples of documents relevant to various life cycle stages and their potential integration into LC-BISs.

Table 5.3: Types and examples of documents and files relevant for a life cycle building information system

| Type of document / file | Examples |
|---|---|
| Planning record | Needs assessments, feasibility studies, and design reports |
| Construction record | Service catalogs, manuals, project management documents, handover and acceptance protocols |
| Transaction record | Documentation of building surveys and due diligence, sales contracts, EPCs |
| Contracts | Lease contracts, financing contracts, insurances |
| Building permit | Planning documents, compliance verification, safety certifications, land register extracts |
| Building product documentation | Data sheets, warranties, maintenance instructions, waste processing incstructions, EPDs |

By supporting the storage, management, and integration of these documents, LC-BISs serve as both data repositories and document management systems, accommodating the diverse requirements of actors throughout the building life cycle.

#### 5.4.1.4 Linked data to external information resources

A LC-BIS is expected to function as a semi-open information system, characterized by fluid boundaries that connect it to other systems and external data sources. Linking data effectively is a key paradigm to ensure data consistency, enhance the overall value of a LC-BIS, and simplify data-sharing processes by reducing the workload associated with traditional data exchange. Instead of comprehensively storing all building-related data, LC-BISs can leverage linkages to make external information resources available in a digital and structured format.

Beyond improving data access and interoperability, linked data are essential for assessments and evaluations, particularly when external parameters serve as boundary conditions for determining indicators. Examples include climate zones, building product data, or benchmarks relevant for sustainability assessments.

Linking external information is particularly beneficial for large datasets that are impractical to replicate or maintain within the LC-BIS and for data owned by third parties. These external resources provide significant value to actors, especially when accessed through seamless integrations that enhance decision-making processes. Table 5.4 illustrates the types of data categories, their specifications, and the benefits of linking external information resources to LC-BISs.

Table 5.4: Overview of different types of linked data in a life cycle building information system

| Data category | Sub-category | Content / function |
|---|---|---|
| Master data | Company registers | Basic information about potential service providers and contractors |
| | Corporate registers | Basic information about potential service providers and constrictors based on internal registers |
| Location data | Cadastral data | Information about the layout of properties |
| | Climate data | Information about the former, current and future climate at the specific location |
| | Data from GISs | Spatial data as a basis for location and market analyses for example |
| Inventory data | Building product and material databases | Information about important characteristics of building products and materials |
| | Building design standards and guides | Assistance in design activities and possible benchmarks |
| Legal data | General legislation | Insights into existing law at the specific location |
| | Building laws and construction codes | Information about the specific requirements on the design, construction and use of buildings including sustainability requirements |
| Economic data | Standards and industry guidelines | Assistance in different tasks related to the specific building |
| | Benchmark data | Possibility to compare the profitability of owning, using or renting a building |
| | Market data | Information as a basis for financial analyses |
| | Commercial registry | Basic information about potential competitors related to the building |
| Performance data | Cluster data sets | Possibility to analyze the performance of building stocks |
| | Benchmark data | Possibility to compare the sustainable performance |

By linking to these external information sources, LC-BISs enhance their role as interoperability tools, ensuring consistency and access to datasets without the inefficiencies of full-scale duplication. In an advanced system, linking can be enabled via linked data and semantic web technology

#### 5.4.1.5 Metadata

Metadata are a fundamental requirement for LC-BISs, ensuring that building-related data are structured, accessible, and interoperable. To support effective information management, a LC-BIS must implement comprehensive metadata strategies that facilitate data discovery, interpretation, and governance.

A key requirement is the systematic definition of relationships between data points, allowing data to be contextualized, linked, and efficiently retrieved. To achieve this, a LC-BIS must:

- Ensure searchability and consistency, enabling users to locate and access relevant datasets efficiently.
- Support interoperability, allowing seamless integration with external information systems and facilitating dynamic updates as data evolve.
- Provide governance mechanisms, ensuring metadata track changes, version histories, and access rights to maintain data integrity and accountability.

To meet these requirements, a LC-BIS must incorporate structured metadata frameworks, covering essential elements such as:

- Descriptive metadata – Titles, classifications, and contextual tags that improve data retrieval and usability. In the context of building-related data, descriptive metadata must also clarify the object of reference, i.e., whether a data point pertains to a property, building, unit, room, or building element. This classification is essential for correct interpretation and linkage of data across spatial hierarchies.
- Administrative metadata – Version tracking, access rights, and timestamps to ensure governance and compliance.
- Technical metadata – Data formats, compatibility requirements, and structural specifications supporting integration across platforms.

Certain metadata elements apply across all data points, such as time of validity or source of the data, while others are specific to particular data types. In the case of inventory data, especially for building elements, metadata should include the status of the data, indicating whether it reflects an as-required, as-designed, as-built, or as-used state. Such distinctions are essential for ensuring correct interpretation and appropriate application of the data across life cycle stages.

To support implementation, an overview of relevant metadata types and their roles in LC-BISs is provided in section D.1. The list includes examples of descriptive, administrative, technical, and provenance-related metadata, among others. These metadata types are not exhaustive but illustrate the range of attributes necessary to ensure that building-related data can be properly classified, interpreted, and used in line with life cycle requirements.

### 5.4.2 Overview on required data points

#### 5.4.2.1 Basis: Taxonomy of building-related data needs

In section 3.3, the data needs associated with essential building-related tasks in the real estate industry were categorized into a taxonomy of building-related data needs. This taxonomy consists of four overarching data categories: master data, inventory data, economic and legal data, and performance data. These categories provide a logical framework for grouping relevant data points and defining the content requirements of a LC-BIS. They reflect the diverse needs of actors and tasks throughout the building life cycle while maintaining the flexibility to adapt to future developments. The premises of this taxonomy were explained in section 3.3.8, while a comprehensive list can be found in section B.7. This classification serves as a foundation for both system design and practical implementations.

#### 5.4.2.2 Minimum data point requirements

While the taxonomy presents a comprehensive overview of potential data points, including all of them in a LC-BIS right away is impractical due to resource limitations and varying actor needs. Consultations with industry experts (section B.1) revealed that, despite differing perspectives, some data points can be regarded as essential core data that every LC-BIS should include from the outset. Establishing minimum requirements provides a manageable foundation for setting up LC-BISs while limiting the effort required for data collection and consolidation. However, the specific effort depends not only on the data points themselves but also on factors such as system functionality, actor-specific needs, and various legal, technical, and organizational boundary conditions.

Several aspects were considered in specifying these minimum requirements, with the overarching criterion being their relevance across building-related tasks. Supporting factors include:

- Frequency of use and updates: How often a data point is needed for decision-making or operations.
- Impact on decision-making: Whether the absence of a data point would hinder critical processes.
- Compliance and regulatory requirements: Legal obligations that necessitate the inclusion of specific data points.
- Cost-efficiency: The balance between the effort required to collect and maintain data and the value provided to system users.

Minimum requirements cannot necessarily be defined at the highest level of the taxonomy but require a closer examination of individual data points or subcategories. Table D.2 indicates which subcategories or specific data points are considered minimum requirements, marking either complete categories or specific data points. The reasoning behind their inclusion is briefly explained, clarifying their relevance for core LC-BIS functions. For example, while only some master data categories are considered essential, specific elements like building identification and usage type are critical. Similarly, legal data related to property rights and building permits are fundamental due to regulatory requirements, while basic inventory data, such as building geometry and dimensions, are indispensable for operational decision-making across various life cycle stages.

#### 5.4.2.3 Extended data point requirements

While minimum requirements define the essential data points necessary for LC-BIS functionality, extended data requirements go beyond these essentials. They are closely connected to specific actor perspectives and tasks throughout the building life cycle and cannot be universally specified. Instead, their relevance depends on the specific context, use case, and organizational priorities. However, maintaining extended data points can provide significant value for advanced decision-making, detailed analyses, and specialized applications.

Several factors influence the inclusion of extended data requirements, including building use and type, organizational strategy, regulatory changes, technological advancements, and specific actor responsibilities.

Certain data categories, though not part of the minimum requirements, can offer significant benefits when maintained in a LC-BIS:

- Master data such as planning and construction records, along with maintenance and real estate management logs, help preserve a seamless history of the building.
- Inventory data can be specified to various levels of detail, but particularly valuable information includes aspects of building geometry, components, services, and functional properties for supporting life cycle tasks.
- Economic data on costs, revenues, and property value are critical for return-oriented real estate management.
- Performance data are important for both operational efficiency and sustainability. This includes energy and resource flow data, which can form the basis for analyses and assessments, particularly for companies subject to non-financial reporting obligations.

The inclusion of extended data requirements should be based on specific actor needs, life cycle tasks, and organizational priorities, as they often require additional effort but can offer substantial long-term value.

## 5.5 Data quality requirements

To meet the needs of information management, LC-BISs must ensure that a range of data-related requirements are fulfilled. These can be subsumed under the broader concept of data quality requirements, which aim to safeguard the overall effectiveness, efficiency, and compliance of the information system. As a result, these requirements can only be fully met in digital implementations of a LC-BIS. While specific data quality requirements may vary depending on the occasion and the actor involved, a general distinction can be made between minimum and extended requirements, each holding different levels of relevance for LC-BISs.

A few earlier examples of approaches to determining data quality requirements for information management and BISs can be found in the literature, including Jylhä and Suvanto (2015, p. 305), Bodenbender and Kurzrock (2015), and KPMG (2021, p. 23). However, these approaches are not directly applicable to the context of LC-BISs due to differing focal points, contextual conditions, and certain limitations.

### 5.5.1 Minimum data quality requirements

One of the primary functions of a LC-BIS is to ensure access to reliable and actionable building-related data for all actors involved in the life cycle. This requires fulfilling several strict data quality requirements that are essential for the system's usability and trustworthiness.

Key aspects include ensuring that data are available and accessible while maintaining appropriate security measures. The system must provide user-specific permissions and efficient retrieval mechanisms, enabling seamless access for authorized individuals while protecting sensitive information. Additionally, data accuracy and currency are vital, as outdated or incorrect data can lead to operational inefficiencies or misinformed decisions. Regular updates and validation mechanisms help maintain relevance and reliability.

Consistency across the LC-BIS is also essential, ensuring that changes made in one part of the system are reflected throughout all related datasets. This avoids discrepancies and maintains coherence across various functions and life cycle stages. Interoperability plays a significant role in facilitating data exchange between systems by adhering to standardized formats and structures, preventing issues related to system lock-ins or incompatibility.

Finally, data security must address concerns around authenticity, confidentiality, and traceability while establishing clear rules around data ownership. These measures help build trust among actors and ensure that sensitive information remains protected.

Table 5.5 clusters these data quality requirements into key dimensions, providing a clearer overview of their associated terms and explaining how they contribute to ensuring the LC-BIS functions effectively across all life cycle stages.

Table 5.5: Clusters, dimensions, and explanations on strict data quality requirements for life cycle building information systems

| Data quality cluster | Associated terms and requirements | Explanation |
|---|---|---|
| Accuracy | Correctness, validity, currentness, originality | Data should be correct, validated, and reflect the original source where applicable. In addition, data must be kept current to ensure relevance over time. |
| Availability | Accessibility, findability | As a data repository, a LC-BIS must ensure that building-related data are both accessible to authorized users and findable through appropriate indexing and search mechanisms. |
| Consistency | Updateability | Data must remain consistent throughout the system, avoiding contradictions or duplication. Suitable mechanisms must be in place to ensure timely and accurate updates whenever changes occur. |
| Interoperability | Compatibility, portability, | Standardized data formats and structures should be applied to ensure compatibility with other systems, enable data reuse, and support seamless |

| | | |
|---|---|---|
| | reusability, unique identification | integration. Unambiguous and persistent identifiers are essential for reliably linking data across systems and life cycle stages. |
| Security | Trust, authenticity, confidentiality, traceability, protection | Data security must be ensured alongside system security. This includes fulfilling key objectives such as maintaining confidentiality, verifying authenticity, enabling traceability of actions, and protecting data from unauthorized access or manipulation. |

### 5.5.2 Extended data quality requirements

While minimum requirements ensure that a LC-BIS can function effectively and reliably, extended data quality requirements are necessary to enhance the system's capacity to support complex tasks and meet specific actor needs. These requirements go beyond core operations and, when fulfilled, can improve how actors interact with and benefit from the system.

A key extended requirement is completeness, which reflects the inclusion of additional data points beyond the minimum requirements (section 5.4.2.2). Achieving a fully comprehensive dataset is neither practical nor necessary for all use cases, but the system should be capable of accommodating more detailed data when needed. Factors such as building use type, ownership structure, and organizational priorities influence the level of completeness required. A flexible LC-BIS structure allows for the integration of extended data points.

Non-redundancy focuses on minimizing unnecessary duplication of data, improving system efficiency and clarity. Some redundancies may be acceptable, particularly when data are stored in multiple formats for compatibility, but consistency must be maintained across all records to ensure data reliability.

Readability and interpretability are important to ensure that data are accessible and understandable for actors with varying levels of expertise. These aspects help ensure that data can be effectively used for decision-making and support diverse tasks across the building life cycle without compromising the clarity or relevance of the information.

Lastly, usefulness ensures that only relevant data are maintained within the LC-BIS. As actor needs evolve, the system should be able to adapt by including data that become necessary for new tasks or emerging regulations, ensuring that information remains applicable and valuable over time.

Table 5.6 outlines these extended requirements, explaining how each contributes to improving the LC-BIS's ability to support diverse tasks and actors across the building life cycle.

Table 5.6: Clusters, dimensions, and explanations on soft data quality requirements for life cycle building information systems

| Data quality cluster | Associated terms and requirements | Explanation |
|---|---|---|
| Completeness | Extensibility | LC-BISs should fulfill minimum content requirements for building-related data while remaining extensible to include additional data when needed. |
| Non-Redundancy | Minimality | Redundancies should be avoided where possible. However, if data are stored in multiple formats within a LC-BIS (e.g., for compatibility or usability reasons), redundancy can be tolerated as long as internal consistency is ensured. |
| Readability | Comprehensibility, understandability, interpretability, clarity | Data should be structured and presented in a way that enables users to clearly interpret their meaning. Comprehensibility may vary depending on the complexity of the data and the expertise of the user. |
| Usefulness | Relevance, efficiency | Only data relevant to the defined scope and system boundaries of the LC-BIS should be retained. Future relevance cannot always be predicted, but data storage should remain focused and efficient. |

### 5.5.3 Quality requirements for specific data points

The level of data quality requirements in a LC-BIS is not uniform across all data points. Instead, these requirements depend on specific factors that influence how strict or flexible the conditions for data accuracy, availability, security, consistency, and interoperability should be. These factors ensure that each data point is managed in line with its relevance, usage, and sensitivity within the system.

The following factors play a central role in determining the specific level of data quality requirements for different data points:

- Level of sensitivity/confidentiality: Sensitive data, such as ownership information or financial records, require higher levels of security, including stricter access controls and encryption. Data ownership and the degree of control also influence the required security measures, ensuring that access rights reflect both legal obligations and operational responsibilities. In contrast, less sensitive information, such as basic building geometry, requires lower levels of protection.
- Time of validity: Data points vary in their relevance over time. Dynamic data, such as energy consumption or emissions, require frequent updates and strict consistency measures to ensure that the information remains accurate and actionable. In contrast, static data, such

as construction year or original design records, have longer validity periods but still require verification following significant changes like renovations.

- Legal obligations for data retention: Regulatory requirements dictate how long certain data must be retained and how easily they should be accessible. Legal documents, compliance records, and permits must adhere to specific retention periods and often require traceability mechanisms that record any changes, ensuring regulatory compliance and auditability.
- Degree of structurization: The structure of a data point influences requirements for readability and interoperability. Highly structured data, such as information stored in standardized formats (e.g., IFC for BIM data), require adherence to strict formatting rules to ensure compatibility with other systems. In contrast, less structured data, such as scanned documents or images, may require additional processing to ensure their accessibility and usability within the LC-BIS.

Each of these factors affects the level of strictness required for the data quality categories outlined earlier. For example, highly sensitive data points demand higher security standards, while data with a short validity period require stronger controls on consistency and regular updates. Section D.3 indicates how these factors apply to particular data points within the taxonomy of building-related data needs.

## 5.6 System-related requirements

Actors impose system-related requirements on LC-BISs to ensure that the system functions effectively, efficiently, and securely while meeting their practical needs. These requirements can be understood as socio-technical requirements, as they reflect both technical and organizational demands. They are closely interlinked with functional, data quality, and content-related aspects, forming a holistic framework for system development and use. Unlike prescriptive technological specifications, system-related requirements allow for technology-neutral implementation, while remaining aligned with the broader objectives of a LC-BIS.

The requirements discussed in this section are partly based on fundamental quality attributes commonly referenced in the literature on ISAs (Sunyaev, 2020, p. 65). Their implementation supports a lean information management approach, aimed at improving efficiency and minimizing waste (Hicks, 2007, p. 234). Comparable approaches to defining system-related requirements can be found in Pfnür (2011, p. 422), Nebauer (2012, p. 54), and Alreshidi et al. (2016, pp. 7–8).

Effectiveness and efficiency are essential for widespread adoption. Actors expect a LC-BIS to deliver its core functions seamlessly, supporting decision-making and information management tasks. Efficiency should not only optimize system operation but also result in measurable benefits over time, such as cost reductions, time savings, or streamlined workflows.

Security is fundamental to building trust among users. Beyond protecting data, the system must also safeguard hardware, software, and all associated resources. Data ownership is a related and equally critical aspect, requiring clear definitions of who owns, accesses, and utilizes the information within the LC-BIS. It reflects the intersection of data-related and system-related requirements and must be addressed explicitly in system design.

Additional system-related requirements include availability, operability, scalability, maintainability, and interoperability. Availability ensures that the system remains accessible and reliable, including in multitenant environments. Operability relates to ease of use and intuitive interaction, enabling diverse users with varying levels of expertise to work with the system effectively. Modularity and scalability allow the system to adapt to specific use cases and expand its scope as needed, supporting a broad range of applications. Maintainability ensures that the system remains functional, secure, and up to date over time, accommodating evolving technological and organizational demands.

Finally, system interoperability ensures that the LC-BIS can interact with other platforms, such as BIM systems, through a robust technical infrastructure that enables seamless communication. While closely related to data interoperability, which focuses on the compatibility and standardization of data content, system interoperability emphasizes the underlying technical architecture, such as APIs and interfaces, that enables efficient integration and collaboration across systems.

Table 5.7: Overview and explanation of system-related requirement on a life cycle building information system

| Requirement | Explanation: A LC-BIS should… |
|---|---|
| Availability, reliability | Have a high level of availability and cope well with multitenancy to ensure a consistent database. |
| Controllability, modifiability, configurability | Enable users the possibility to navigate through the system according to their access rights and modify the use of the system according to personal usability preferences. |
| Effectiveness | Ensure that main functions to support information management goals are provided. |
| Efficiency | Enable an efficient use of the system which should lead to efficiency increases in information management in general. The benefits of using a LC-BIS must outweigh the costs over time. |
| Interoperability | Enable an efficient collaboration with other information systems. |
| Maintainability | Be maintainable so that eventual quality issues and necessary improvements can be handled. |
| Modularity, granularity | Follow a modular approach to provide a structured view on data and system functions and to take in a certain level of abstraction. This goes along with the requirement to consider different objects of considerations and different system boundaries. |
| Operability, Ease of use | Be easy to use and operate for the target users. |
| Scalability, expandability | Be scalable so that a specific LC-BIS can be enriched with additional functions and data. Additionally, the concept itself and built-on business models should be scalable so that a wide adoption can be achieved. |

| | |
|---|---|
| Security, trustworthiness | Ensure the security of the system, involved data and actors while using the system. This involves a strategy and measures to protect hardware, software, and information resources. |
| Supportability | Support its users in tasks they can perform and also support them actively through automation. |

By meeting these system-related requirements, LC-BISs can provide a robust foundation for managing building-related information, offering reliability and flexibility to support diverse actors and tasks throughout the building life cycle.

## 5.7 Summary requirement profile

Several insightful aspects were outlined in this section to stress critical aspects that must be considered for a LC-BIS.

- The definition of a BIS has been refined to specifically refer to a system that holistically supports information management throughout the life cycle of individual buildings, termed a "life cycle building information system" (LC-BIS).
- The core function of a LC-BIS is to serve as a data repository, storing building-related data consistently and making it accessible to actors for tasks across the building life cycle. This approach benefits the integration of data that would otherwise remain fragmented across various information systems. It also fosters a standardized data collection, data sharing, data quality control, and decision making. These functions are predominant through specific life cycle stages and tasks. Data availability and quality offer significant potentials to enable data analytics functions that are specifically beneficial to industry experts.
- The data content of a LC-BIS should lean on the data needs for building-related tasks as indicated by the taxonomy developed in section 3.3. There is no universal approach to indicate which data are relevant but it is beneficial to orientate on minimum data requirements first. These are crucial to facilitate core functions of a LC-BIS.
- To meet user needs effectively, LC-BISs must fulfill several data quality and system-related requirements. These include ensuring data availability, consistency, security, and interoperability at both the data and system levels. It becomes evident that meeting these requirements depends on a certain degree of standardization in both content and functionality of LC-BISs.

To evaluate the capability of existing BISs to meet these requirements, a fact sheet was developed. It summarizes the most important aspects of the requirement profile, complemented by general contextual information. The aim was to design a fact sheet that is sufficiently detailed yet practical, providing an accessible overview for assessing BIS suitability (Figure 5.5).

Typical terms used to describe the type of BIS

Goals pursued with the use of the BIS

Description of drivers for the development of the system

Main functions met by the BIS

Life cycle stages covered

Main data categories covered

Conclusion on suitability as LC-BIS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Term(s)** | **(Digital) building passport, digital building logbook, electronic building passport housing file** | | | | | | | |
| **Goals** | Comprehensively store and manage building-related data throughout the life cycle of a building, make it available to different actors when needed, and thus offer potentials to drawing insights through analyzing and using data | | | | | | | |
| **Background and drivers** | Concept and idea already exist for several decades, but have not found wide adoption in the real estate industry; new approaches focus on integration of suitable technologies to make use of digitalization and automation; increasing demand in different domains of the real estate industry, based on information management issues, such as lack of transparency, poor information quality, poor data sharing | | | | | | | |
| **Main functions** | ☒ | Data and document repository | ☒ | Data sharing platform | ☐ | Digital copy | ☐ | Action plan and guide |
| | ☐ | Data creation and collection aid | ☒ | Quality management system | ☐ | Assessment tool | ☐ | Other: |
| **Life cycle stages** | ☒ | Development | ☒ | Construction | ☒ | Use | ☒ | End-of-life |
| **Data categories** | ☒ | Master data | ☒ | Inventory data | ☒ | Legal and economic data | ☒ | Performance data |
| **Suitability as LC-BIS** | Very high, since many typical issues in information management can be addressed | | | | | | | |

Figure 5.5: Explanation of categories applied in fact sheets for building information systems

Chapter 6 provides further details on how fact sheets are used to analyze various BISs.

# 6 Analysis of existing building information systems

*This chapter deals with existing approaches for BISs and related information management solutions. The current state of knowledge on BISs is analyzed in detail by conducting a hybrid research approach combining a systematic and targeted literature review. The review will include academic concepts and solutions from the industry. First, the methodology for the literature review will be explained and the results will be quantitively analyzed using appropriate metrics (section 6.1). Second, several sections will deal with relevant BISs based on the findings of the literature review (sections 6.2 to 6.5). The specific BISs will be analyzed in depth and for each type a profile will be given in the end that checks to which extent the respective system fulfills the requirements on BISs from chapter 5. In the end, the findings are compared and discussed (section 6.6). The aim is to answer research question 2 by evaluating whether existing BISs meet the requirement profile for LC-BISs, and if so, to what extent they do.*

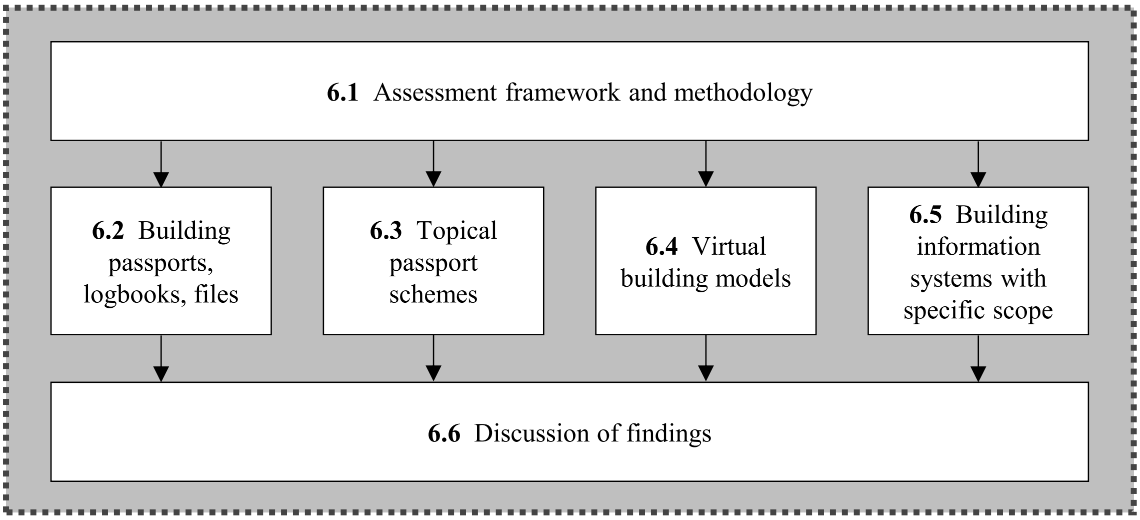



Figure 6.1: Structure of chapter 6

# 6.1 Assessment framework and methodology

## 6.1.1 Identifying relevant systems: challenges and research approach

The identification of relevant BISs with potential for life cycle applications required addressing several challenges inherent to the field. The diversity and abundance of existing systems, coupled with fragmented terminologies and differing focal points, made a targeted and comprehensive evaluation essential. These challenges are compounded by the specificity of building-related information management, which has resulted in a proliferation of siloed solutions. Furthermore, many tools and systems are underrepresented in academic literature, necessitating an approach that goes beyond traditional scholarly sources to achieve a holistic understanding.

To tackle these challenges, a hybrid research approach was employed. This approach combines a systematic literature review with a targeted, non-systematic search and expert knowledge. The systematic review provided a structured framework for identifying systems discussed in academic publications, while the targeted search expanded the scope to include grey literature such as technical reports, government documents, white papers, and theses. Expert insights gathered through interviews (section B.1), along with the author's prior experience, added a critical layer of depth to the evaluation process.

By integrating these methods, the analysis ensured a comprehensive foundation for assessing the potential of BISs to serve as LC-BISs. This hybrid approach also facilitated the identification of terms and search strings tailored to the field, ensuring the systematic review was both focused and robust.

## 6.1.2 Systematic literature review

The systematic literature review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Page et al., 2021). as a methodological framework. Additional guidance for specifying the review process was derived from Wohlin (2014), Snyder (2019), and Gernler (2023). This structured approach ensured transparency and reproducibility in identifying and evaluating relevant academic contributions.

The first step involved specifying relevant terms and developing a search string designed to cover a wide range of potentially relevant literature (Figure 6.2). The aim was to ensure inclusivity while avoiding an overwhelming volume of results with limited relevance. For instance, while academic publications on passport schemes are relatively rare, the literature on virtual building models such as BIM and digital twins is vast. Consequently, the search string was carefully refined to include not only general terms like "BIM" and "digital twins" but also keywords tied to life cycle tasks essential for LC-BISs, such as "building life cycle management." This refinement ensured a focused scope addressing the objectives of the study.

**Search string**

*"building passport" or "digital building logbook" or "building logbook" or "renovation passport" or " material passport" or "resource passport" or "housing file" or ("digital twin" and ("construction management" or "facility management" or "asset management" or "AEC")) or ("BIM software" and ("construction management" or "facility management" or "asset management" or "AEC")) or "common data environment" or "building lifecycle management" or "building data management" or "collaborative BIM" or "real estate information system" or "real estate management system" or "CAFM system"*

Figure 6.2: Search string applied for the systematic literature review

The databases Scopus and Web of Science were selected for their extensive coverage of real estate-related topics and advanced functionalities for processing results. The initial search was conducted on May 13, 2023, and subsequently updated on January 25, 2025, to incorporate the latest publications. The initial search yielded over a thousand results (Figure 6.3). Papers were excluded based on language and accessibility, with additional exclusions for irrelevant subject areas. Following this, duplicate entries were removed, and titles, abstracts, and keywords were screened to refine the dataset further. Full-text screening eliminated additional papers, leading to a final dataset of 341 relevant publications. Forward and backward snowballing techniques were applied as a final step to identify relevant references and citations, enriching the dataset further.

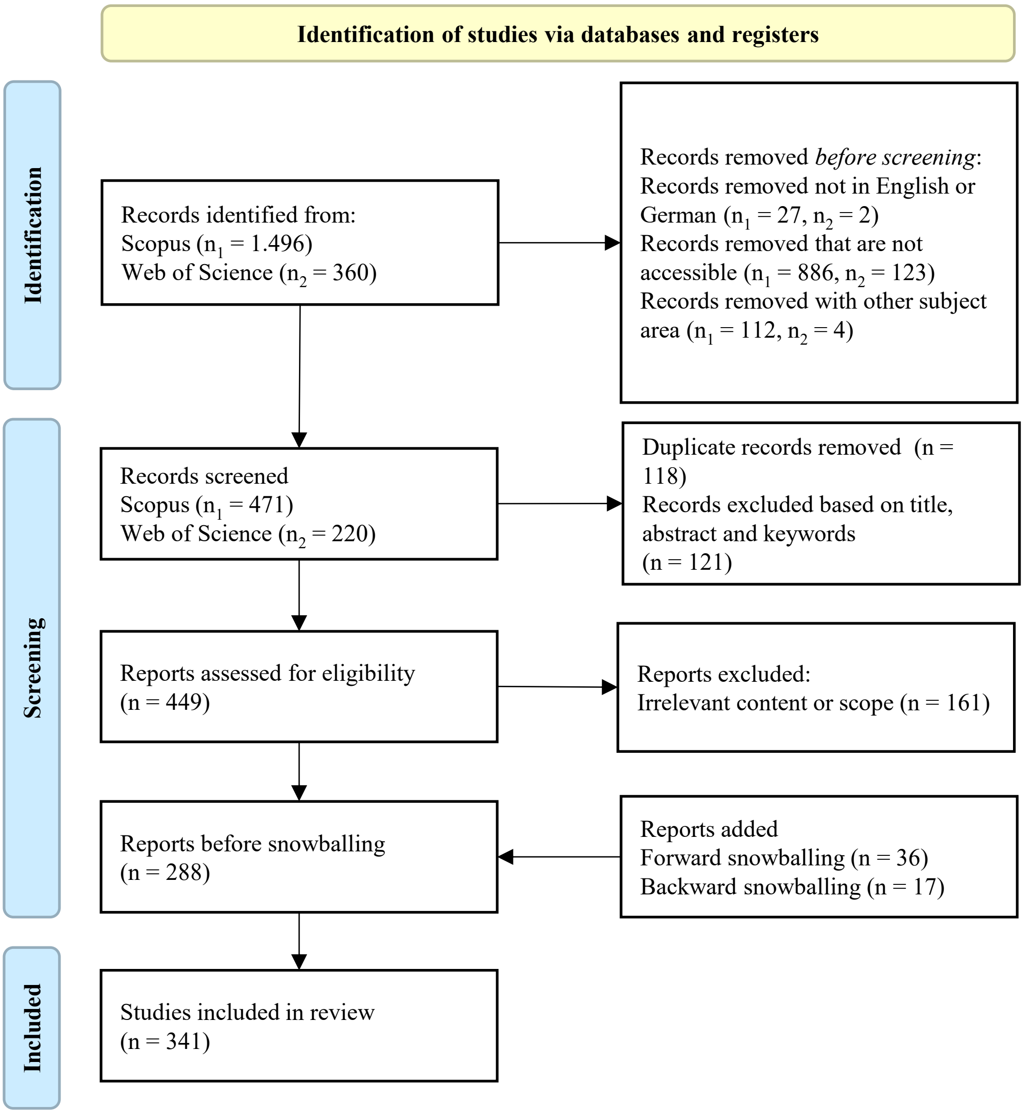



Figure 6.3: Steps of the systematic literature review based on Page et al. (2021)

To gain additional insights into the dataset, the publication years of the identified papers were analyzed. The results reveal a strong increase in publications over recent years, particularly since 2020 (Figure 6.4). This trend reflects the growing academic interest in topics related to digitalization, the increasing adoption of BIM and digital twins, and the broader evolution of building information systems. By contrast, earlier decades exhibit a relative absence of literature, underscoring the novelty of these topics in academic discourse.

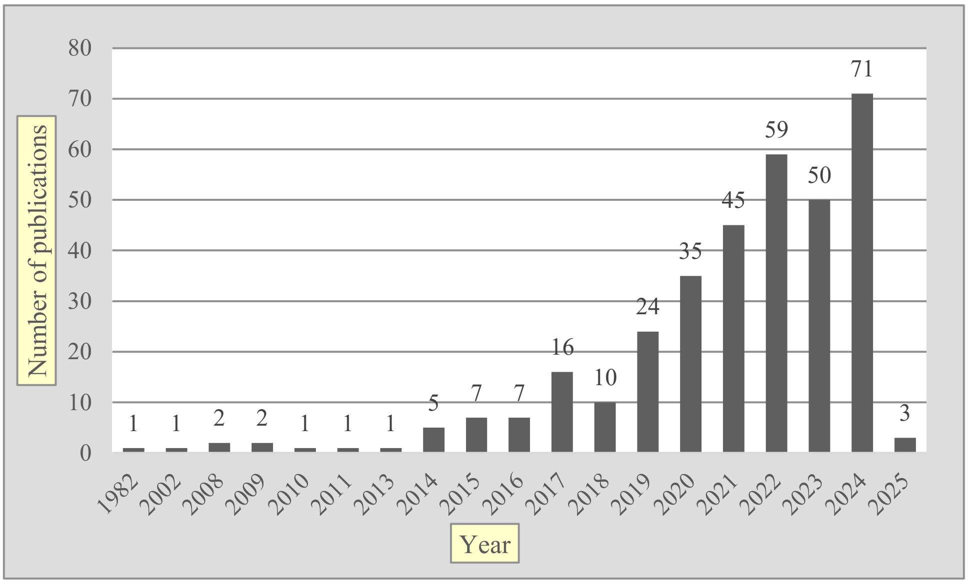



Figure 6.4: Number of publications identified in the review per year

The main topics of the identified papers were also examined. BIM and digital twins dominate the literature, accounting for over 70 % of the publications (Figure 6.5). In contrast, aspects related to building life cycle management, facility management, and asset management represent smaller portions, while passport schemes are a minority focus. This imbalance reflects the broader trends in academic research, with significant emphasis on digitization and technological innovation.

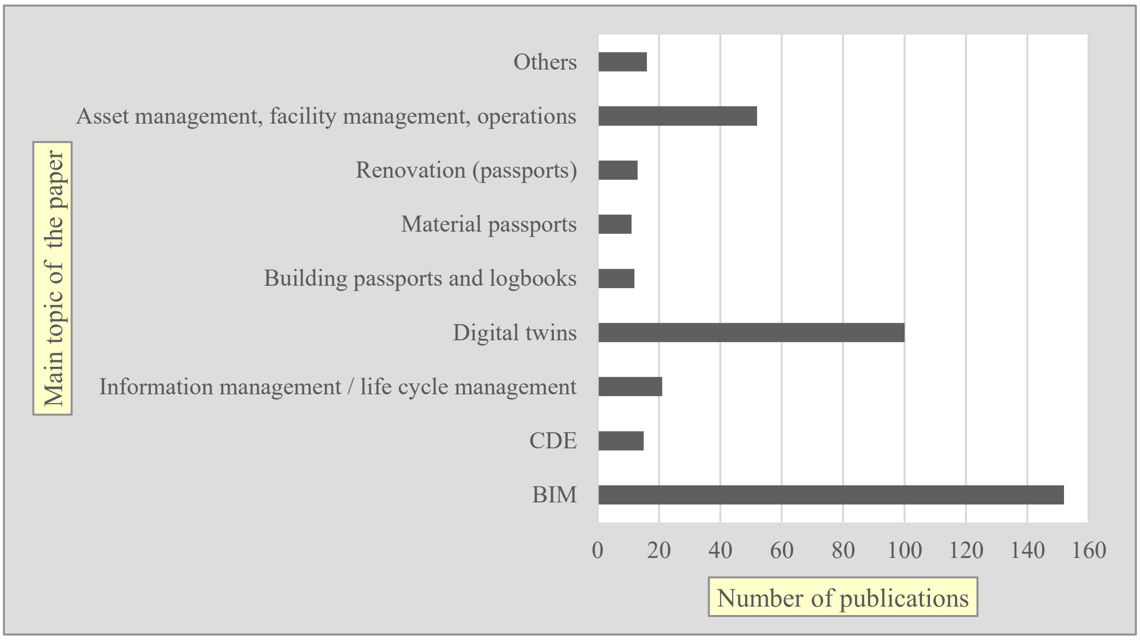



Figure 6.5: Main topics of the papers identified in the literature review

### 6.1.3 Targeted literature review and expert interviews

While the systematic review provided a strong foundation, it revealed gaps in certain areas. Specifically, some types of BISs, such as passport schemes and practical implementations, were underrepresented. To address these gaps, a targeted literature review was conducted, supplemented by expert interviews and the author's prior experience. In a later phase, expert interviews were used to validate key findings and retrospectively complement the analysis with additional practical insights (section B.1).

Grey literature, including technical reports, white papers, and documents from EU-funded research projects, was a critical source of insights, particularly for passport schemes and related concepts. Additionally, books and industry-specific publications were consulted for more in-depth discussions on BIM and digital twin technologies. For systems such as real estate portfolio management tools and ERP systems, which are commonly applied in practice but rarely addressed in scholarly works, expert input provided further context.

Standards and guidelines from international and national standardization committees also played a key role. These documents provided critical frameworks for evaluating the relevance and applicability of different systems in the context of life cycle-oriented BISs. By integrating these diverse sources, the targeted review added breadth and depth to the findings of the systematic review.

The targeted literature review and expert interviews resulted in the inclusion of an additional set of sources, quantified at n = 177. These sources contributed unique perspectives, such as insights into implementation challenges, policy influences, and technical specifications not covered in the academic literature.

### 6.1.4 Approach to analysis

The analysis of findings from the literature review was structured to evaluate the potential of identified systems to serve as LC-BISs. To achieve this, the systems were organized into clusters based on shared characteristics such as terminology, primary functions, and the specific tasks they address. This clustering approach facilitated a systematic and focused evaluation of their relevance and functionality in the context of the requirement profile outlined in Chapter 5.

The identified systems were grouped into four main categories:

- Building Passports, logbooks, and files: These systems were examined for their historical development, current applications, and alignment with life cycle requirements. The analysis considered their origins, the motives of the involved actors, and their broader implications in information management.
- Other passport concepts: This group reflects the growing popularity of passport systems across various domains, including material passports and renovation passports. These tools were analyzed to assess their scope, functions, and relevance to life cycle information management. The diverse approaches were reviewed to highlight trends and shared characteristics.

- Virtual building models (BIM and digital twins): Representing the largest category in the literature, these systems were analyzed for their ability to enhance life cycle information management. Their functions and applications were assessed, focusing on their suitability for LC-BISs and their potential for supporting advanced digitalization in the built environment.
- Task-specific tools: This group includes systems with specialized applications, such as facility management tools, Enterprise Resource Planning (ERP) systems, Building Automation and Management Systems (BAMSs), and cadastral systems. These tools were evaluated for their complementary roles in supporting life cycle-oriented functions.

Each group was systematically assessed against the requirement profile outlined in chapter 5. This evaluation focused on their ability to support essential life cycle tasks, including the collection, storage, sharing, and analysis of building-related data. By comparing the systems' capabilities and functionality with the requirements, the analysis highlighted both their potentials to serve as LC-BISs and the insufficiencies or gaps that might hinder their suitability. For systems demonstrating significant potential to function as LC-BISs, fact sheets were provided to summarize their characteristics, strengths, and limitations in a concise and actionable format.

This structured approach provided a clear framework for comparing the diverse systems and tools, ensuring a comprehensive understanding of their relevance and limitations. By identifying both their strengths and their insufficiencies, the analysis offers valuable insights into areas where further development is needed to realize the concept of LC-BISs.

## 6.2 Building passports, logbooks, files

This section provides a detailed analysis of building passports, logbooks, and files based on insights from the literature review. The primary objective is to evaluate how well these tools meet the LC-BIS requirements outlined in chapter 5, with a particular focus on their various functions (section 6.2.3). Given the relatively ambiguous context of these tools compared to others, the review also incorporates a historical perspective (section 6.2.1) and discusses current approaches and trends (section 6.2.2).

### 6.2.1 Historical background

#### 6.2.1.1 Early proposals

The idea of building passports (BPs) already exists for several decades with the first mentioning of the term in the literature originating from Eichstädt (1982, p. 180). However, even though a BP was introduced as an aid in maintenance planning in this paper, no further specification has been given on the concept. Further evidence on the early interest in the topic is provided by Blum (2009, p. 158) who cites Klaus Töpfer, former German Federal Minister for Construction, in a statement about the relevance of BPs: According to Töpfer (1997, p. 603, as cited by Blum (2009, p. 158)), a BP should communicate comprehensive building-related information and increase transparency of technical properties. He suggested a voluntary use by practitioners.

A first more thorough explanation of what a BP actually is and how it works can be found in a government report on sustainable development in Germany (section E.1.1). In this report, a BP is described as a tool that ensures the quality of building functionality, increases transparency in life cycle costs and valuation, and enables the investigation on harmful substances (German Parliament, 1998, pp. 180–181). Further suggestions were made on how the adoption and use of building passports could function as a business model for architects and on the potential benefits for a harmonization of environmental, economic, and social objectives (German Parliament, 1998, p. 181).

In Germany, BPs were conceptualized based on the existing ideas by a proposal of the government which was represented by a hardcopy document that building owners could fill in with information on their building (Ministry of Transport, Building and Housing, 2001). This included, among other things, general information about the ownership, the regulatory context and the plot, as well as information about the structure of the building including associated functional characteristics (section E.1.2). The focus was predominantly on newly constructed buildings and their functional properties. The proposal for a BP became an integral part of the housing file ("Hausakte"), which exceeded the content of the BP scheme by integrating other documents and information from the construction stage, and by introducing a documentation for the use stage (section E.1.3). Within the housing file, the voluntary use of the BP is proposed and it is pointed out that the housing file should not replace existing legally binding certificates (Bundesministerium für Verkehr, Bau- und Wohnungswesen [BMVBW], 2004).

In expert interviews it was found that creating and maintaining housing files in the form of analog document collections was a regular activity in real estate companies in the 1990s and eventually even earlier already. These housing files did not follow any specific standard but were organized based on the preferences of individual employees in housing companies. The storage of relevant documents concerning a building at one specific place, however, was associated with clarity and effectiveness.

In other countries, comparable concepts emerged during the early 2000s. In the UK, building logbooks were introduced as part of the national building regulations in 2002. This initiative aimed to enhance the understanding of building owners and occupants regarding the structural and operational characteristics of their properties, particularly concerning energy efficiency (United Kingdom Government, 2002). Another objective was to provide more comprehensive information to actors involved in real estate transactions. Consequently, the "Home Information Pack" (HIP) was established as a mandatory instrument in 2007. Comprising documents such as a Property Information Questionnaire, an EPC, and Land Registry records, the HIP sought to equip prospective buyers of residential properties with critical information provided by sellers. However, the HIP was discontinued in 2010 following criticism over the additional costs it imposed on property sales (House of Commons Library, 2010). Another development in the UK included the development of a template for building logbooks by Chartered Institution of Building Services Engineers (CIBSE) in a similar fashion than the housing file in Germany (Jones, 2006).

The concept of BPs first became a research subject in the work of Lützkendorf (2000, p. 52), who regards a BP as an object documentation that can be interpreted as a manual for building use. Planers, surveyors, or engineers should establish a BP after construction and hand it to the building owner so that the information is available in modernizations or transactions, for example. He proposes a modular approach to structure the content with the possibility to integrate documents such as EPCs (Lützkendorf, 2000, p. 52).

A slightly different take on building passports was made by Andreas Blum, who lays down a foundation in several research papers (Blum, 2001a, 2001b, 2002, 2009). While he describes BPs initially either as a certificate with the most important performance characteristics or a collection of building-related documents, a new meaning was derived in a trial for the German federal state Schleswig-Holstein. Additional to the basic interpretation as documentation, BPs were supposed to function as a quality label (Blum, 2002). This function, however, was never fully realized due to the dedicated development of green building certification systems.

#### 6.2.1.2 Recent developments

Judging by the number of sources identified, the further adoption of BPs and similar tools stayed low throughout the 2000s and early 2010s (Figure 6.6). While other instruments and tools, such as EPCs and green building assessment system were established with increasing popularity, BPs were mentioned only in a few studies including Rohde et al. (2011), Virta et al. (2012), and Reisinger et al. (2014).

The number of publications began to rise significantly from 2016 onward, coinciding with efforts by the EC to enhance both the energy efficiency and information availability of the European building stock. Based on results from research projects, it was realized that this requires a tool to comprehensively manage building-related information. Thus, the EC introduced a new term: “Digital Building Logbook” (DBL). The idea is more or less the same as it has been for BPs or housing files for years, but the focus was shifted to a digital format. From then onwards, the functionality of DBLs was explored simultaneously to the role of tools with a more dedicated focus on energy renovations, such as renovation passports (section 6.3.2).

Another important parallel driver for DBPs/DBLs and for passport concepts in general originated in the pursuit of fostering circularity in the construction and real estate industry. The objective here was and is to enhance the availability of information regarding the materiality of buildings throughout the entire life cycle. Preliminary research in this area can be found in Reisinger et al. (2014), who investigate the options for developing a building material information system either by integrating a material data sheet within a more thorough BP/housing file (section E.1.4) or by adopting a solution in BIM. In retrospect, the Austrian report could be regarded as a significant contribution to the academic discourse. However, it may also have contributed to the ambiguity surrounding the original function of BPs in comparison to more specific systems, such as material passports (section 6.3.1).

A significant milestone in research on BPs and DBLs was achieved through technical reports published by the EC (Carbonari et al., 2020; Dourlens-Quaranta et al., 2020; Volt et al., 2020). Together with the practical guidelines on BPs provided by the Global Alliance for Buildings and Construction (GABC) (Hartenberger et al., 2021), these publications played a pivotal role in accelerating research efforts. By establishing a shared understanding of the concepts, they laid a strong foundation for advancing further investigations in the field.

Since then, publication density increased significantly with more and more researchers dealing with the topic. Alonso et al. (2023), for example, carried out a systematic literature review to summarize the current state of knowledge with a focus on DBLs. Especially the possibilities of implementing DBLs as a useful tool not only for practitioners, but also for the public sector including the perspective of the EC have been investigated. The EC continues with its efforts in the field leading to publications from own research projects and the funding of complementing research projects (section 6.2.2.1).

#### 6.2.1.3 Milestones of building passport development

The various phases and most significant contributions in the development of BPs can be summarized in a timeline (Figure 6.6).

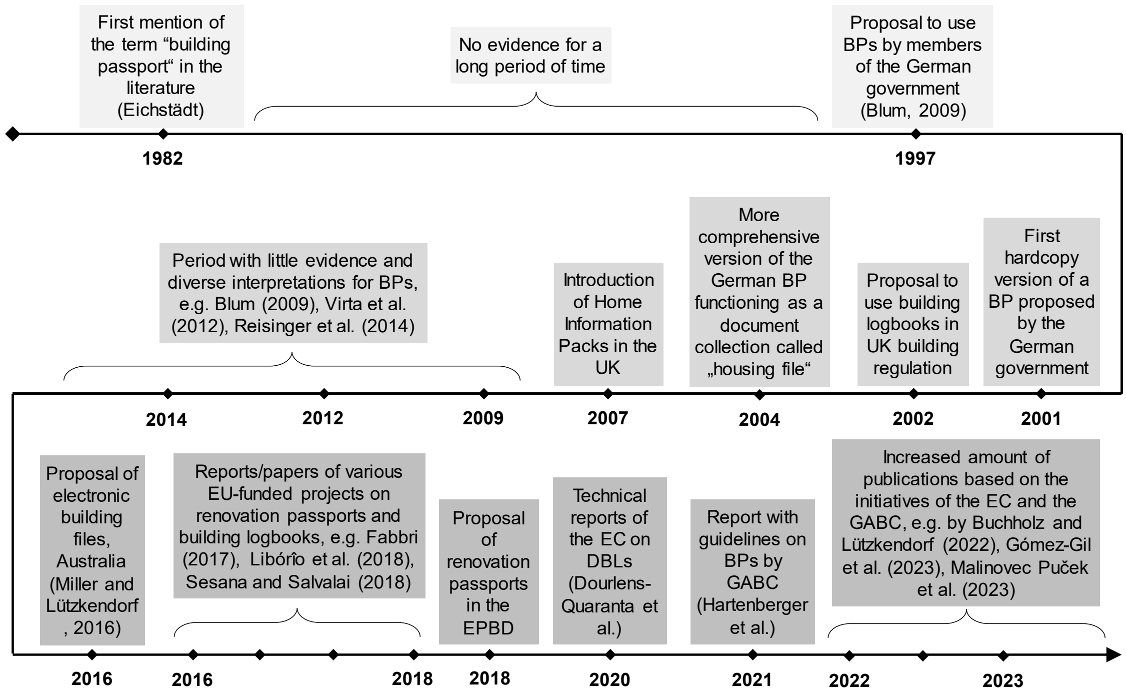



Figure 6.6: Milestones of building passport / logbook development (Buchholz & Lützkendorf, 2023, p. 909)

## 6.2.2 Approaches and trends

#### 6.2.2.1 European commission initiatives

As stated in the historical background, the EC played a substantial role in pushing the concept of BPs and DBLs forward. It funded several research projects in the period between 2017 and 2020, aiming to explore mechanisms such as renovation passports and advancements in EPCs to promote energy renovation across the EU. These projects highlighted the need for a comprehensive tool that consolidates all essential information required for making energy performance-related decisions, which was then called "digital building logbook". Section E.1.5 provides an overview on these projects and how they treated DBLs in their considerations.

Parallel to these projects, the EC carried out own research efforts, which resulted in their pivotal publications (section 6.2.1). Among other things, the EC investigated industry applications that facilitate the management of building-related data. In addition, industry representatives were interviewed through expert workshops and online surveys to determine basic requirements and key characteristics of a DBL. These insights were used for the definition attempt by the EC:

> *“A digital building logbook is a common repository for all relevant building data. It facilitates transparency, trust, informed decision making and information sharing within the construction sector, among building owners and occupants, financial institutions and public authorities[…]” (Volt et al., 2020, p. 12)*

This marks only the first of three paragraphs from the definition, while the others go into more detail which data and functions a DBL should contain. While the study could indicate the need for such a tool in the industry, it also revealed several challenges and research gaps for the topic. Several issues were dealt with in succeeding studies by the EC:

- EC (2022): Within this report, it was analyzed how databases in different EU countries, including Estonia, France, and Italy, that contain data about single buildings meet selected data-related requirements posed on a DBL
- EC (2023): The report “Technical guidelines for digital building logbooks” builds on the findings from earlier DBL studies and makes proposals about the functions and practical implementation of DBLs with a focus on the technical perspective. It primarily addresses EU member states and how those can introduce DBLs under a common European framework.
- Böhms et al. (2023) lay down an approach for a data model for DBLs as addition to the technical guidelines (section 6.2.3).

In a new set of research projects funded by the EU, DBLs often take in a central role (Table 6.1). Most of these projects are not finished yet, but already produced some results to date. It can be observed that these projects, compared to earlier projects under the EU, take the relevance of DBLs as given and try to investigate their role in different contexts. This includes the testing of practical implementations of new DBL functions (Koronen et al., 2024, p. 4), the integration of important technologies, such as APIs (openDBL, 2024a) or blockchains (Buildchain, 2024), the development of tools for a job-sharing approach with DBLs in order to pursue sustainability goals (Chronicle, 2022) or digitization efforts (Digibuild, 2022), and the connection to a harmonized sustainability assessment process in the EU (Gyuris et al., 2023).

Table 6.1: Overview on current European research initiatives dealing with digital building passports and logbooks

| Project name | Dates | Original goal and focus | Reference to DBLs and DBPs | Source |
|---|---|---|---|---|
| Demo-BLog | 2023-2026 | Exploration of practical applications of DBLs based on pilot projects and with a focus on specific functions | DBLs as inherent part of the project | Koronen et al. (2024) |
| OpenDBL | 2024-2026 | Development of a DBL solution as API and application in pilots | DBLs as inherent part of the project | openDBL (2024a) |
| EUB Superhub | 2021-2024 | Development of a platform including a methodology to monitor buildings throughout their life cycle to harmonize energy assessments in the EU | Creation of a DBL as part of the project | Gyuris et al. (2023) |
| Buildchain | 2023-2025 | Creation of a BIM-based decentralized knowledge platform with the help of blockchain technology | Interpretation of the developed solution as DBL | Buildchain (2024) |
| DigiBUILD | 2022-2025 | Development of cloud-based digital tools for data analytics to foster smart buildings and overcoming of data silos | DBLs/DBPs as important information source and implementation in pilots | Digibuild (2022) |
| CHRONICLE | 2022-2025 | Development of tools to improve building performance against sustainability targets with a focus on energy efficiency, comfort, and well-being | DBLs as one output of the project | Chronicle (2022) |

While already being formally integrated within the EPBD as a tool to store building-related data, ensure access to renovation passports, and provide information for national building stock databases (European Parliament and Council of the European Union, 2024), it is very likely that the EC will continue to focus on DBLs.

#### 6.2.2.2 Industry and policy approaches

DBLs and DBPs have not only been a subject of European initiatives but also of actors from the real estate industry and national governmental organizations. The EC analyzed a collection of different initiatives as part of its research on DBLs. The findings included aspects such as a classification according to the maturity level of concepts, an evaluation of the incorporated data categories and functions, an assessment of the level of digitalization, as well as the adoption level for different types of buildings. In total, 40 initiatives were examined including several projects of the Horizon 2020 funding program. The main results can be summarized as follows:

- Most initiatives were in an operating stage at the timing of analysis and the majority of those (14 of 21) were public initiatives, with ten of the 14 being mandatory.
- The majority of initiatives is applicable to individual residential buildings (90 %), while less apply to other types of buildings like multi-apartment buildings, office buildings, or public buildings (range from 48 to 67 %)
- There are different levels of digitalization among the examined concepts. While some still work based on hardcopy documents others are fully digitized with all information accessible online.
- None of the initiatives covers all data categories that have been identified as relevant within the study of the EC. There is much variety concerning the scope of respective concepts. Data categories that were covered most were "building descriptions and characteristics" as well as "equipment, with descriptions and designs" (86 % each). Categories that were hardly covered included "dynamic data" (5 %) or "3D/BIM models of the building" (19 %).
- The same aspect accounts for the identified functions: Most of the concepts provide "building and administrative information" (86 %) as well as "construction information" (71 %) according to the covered data categories, but only a few generate "automatic input from 3D/BIM models" or provide "alerts and updates on the performance/condition" (5 % each).
- 70 % of the initiatives follow a data-centric approach with specific data fields, while 10 % rely on general data categories and 20 % following a document-oriented approach (Carbonari et al., 2020, pp. 7–11).

It can be assumed that the developments in this area are very dynamic which means that new initiatives are established frequently while existing initiatives stop or their concepts evolve. This aspect especially accounts for private initiatives from the industry. Therefore, the overview in sections 0 (policy initiatives) and E.1.7 (industry initiatives) might only be up-to-date for the moment.

It can be observed that initiatives from private institutions and those from governments are usually driven by different motivations. Private initiatives, such as CAPSA (2024) based in Germany, Property Log Book (2023) based in the UK, or Produktkollen (2023) based in Sweden, are typically based on business models, in which the actor that developed a DBP solution wants to be compensated for the products and services offered. Governments on the other hand, who try to advance the topic further, follow goals in their role as legislator which includes:

- Improve the availability of data regarding the national building stock,
- Increase transparency in real estate transactions,
- Foster building renovations by supporting building owners in decision-making,
- Combine tasks of land management and management of the building stock,
- Stimulate circularity in the construction and real estate industry.

Examples for DBP/DBL initiatives from governments include the Electronic Building Passport in Australia (Miller & Lützkendorf, 2016), the Home Report in Scotland (Scottish government, 2020), or the Electronic Building ID in Greece (Ministry of the Environment and Energy, 2021). More and more, private initiatives, such as the Platform CB'23 in the Netherlands (Platform CB'23, 2022), take in a specific role in advancing passport concept, either in conjunction with governmental motives or by intrinsic motivation. Oftentimes, it is not fully clear, whether an initiative is driven by private or public institutions. In some cases, an initiative can be triggered by public institutions and then be implemented as a business model through private organizations.

#### 6.2.2.3 Current research approaches

Along with the efforts within the European context, DBPs and DBLs gained significantly more attention from researchers and academic institutions. This includes several publications in which the author was included. In some cases, research papers are closely connected to the research initiatives funded by the EU. The focus of current approaches includes:

- Analysis of the historical background of BPs, e.g. in Buchholz and Lützkendorf (2022a, pp. 2–3), Buchholz and Lützkendorf (2023, pp. 907–909), Malinovec Puček et al. (2023b, p. 2), Leindecker et al. (2025, pp. 511–513)
- Discussion of terms, e.g. in Gonçalves et al. (2024, pp. 230–231), Tuscher et al. (2024, p. 1087)
- Specification of functions and processes, e.g. in Gómez-Gil, López-Mesa, and Espinosa-Fernández (2022), Mêda Magalhães et al. (2022), Gómez-Gil et al. (2024, p. 1), Mêda et al. (2024, pp. 11–13)
- Specification of data models and contents, e.g. in Dejaco et al. (2020, p. 257), Malinovec Puček et al. (2023b, p. 13)
- Analysis of relevant technologies and stressing the relevance of digitization, e.g. in Gómez-Gil, Espinosa-Fernández, and López-Mesa (2022), Al-Sadoon et al. (2023, p. 681)
- Connections and job-sharing possibilities between DBPs and other tools, e.g. in Buchholz and Lützkendorf (2022a), Gómez-Gil et al. (2023), Malinovec Puček et al. (2023b, p. 11)

The findings of the listed research papers will be used to analyze the suitability of DBPs/DBLs as a LC-BIS (section 6.2.3).

### 6.2.3 Scope and functions

#### 6.2.3.1 Main functions

A majority of publications refer to DBPs/DBLs as long-term data repositories that store all building-related data assumed to be relevant for information management in building-related processes and tasks (Hartenberger et al., 2021, p. 14; Toth et al., 2021). Some publications use synonyms for “data repository” such as “information container” (Hartenberger et al., 2021, p. 15), “archive” (Signorini et al., 2021, p. 2), or “object documentation” (Blum, 2001a, p. 12; Lützkendorf, 2000, p. 52).

DBPs/DBLs are interpreted as data sharing platforms too. They are designed to provide building-related data when needed to the involved actors (Dourlens-Quaranta et al., 2020, p. 32; Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 5; Hartenberger et al., 2021, p. 14). In some cases, DBPs/DBLs have been perceived as rating systems and quality labels. For instance, Blum (2001a, p. 12) proposes to comprehend BPs as a combination of object documentation and quality label. This was before green building certification systems were developed and established themselves as an instrument to assess and communicate the sustainable quality of buildings.

Throughout the years, further evidence exists on the interpretation of DBPs as an assessment tool (dos Santos Gonçalves et al., 2022; dos Santos Gonçalves et al., 2021; Virta et al., 2012). The majority of recent studies, however, regards DBPs/DBLs assessment functions as additional functions based on the availability of data. Dourlens-Quaranta et al. (2020, p. 30), for example, identify the estimation of environmental impacts and the possibility for benchmarking as relevant features based on an expert survey. Malinovec Puček et al. (2023a, p. 9) go one step further and define ratings in several domains such as EPC, smartness, or overall sustainability as essential functions.

Other functions specified for DBPs/DBLs in the literature include the following:

- DBPs/DBLs are expected to share functions of quality management systems, e.g. by automatically sending alerts or notifications regarding resource consumption habits or maintenance needs (Dourlens-Quaranta et al., 2020, p. 30). Additional quality-related functions include the tracking of progress of decarbonizing buildings and building stocks with the help of indicators (Gómez-Gil et al., 2024, p. 3) and the facilitating of a digital building permit process (Mêda et al., 2024, p. 11).
- DBPs/DBLs are not interpreted as virtual building models. However, Dourlens-Quaranta et al. (2020, p. 30) identify the automatic input from virtual building models, i.e. BIM model and digital twins, to DBLs as the most demanded function in an expert survey. This raises questions about the differences, similarities, and job-sharing possibilities between virtual building models and DBPs/DBLs.
- DBPs/DBLs are not primarily intended to generate data for active decision support of actors. However, if building-related data are available in a sufficient quality, they can employ functions to create new data or reorganize it in the form of indicators, documents, or action plans, for example. They can also integrate functions from other tools, such as renovation roadmaps or maintenance plans (BMVBW, 2004; Dourlens-Quaranta et al., 2020, p. 17; Gómez-Gil et al., 2023, p. 3).

Recent studies increasingly explore an extended range of functions for DBPs/DBLs, particularly focusing on how available building-related data can be leveraged through advanced data analytics. While this trend highlights additional benefits, it also shifts the emphasis away from the system's broad applicability across all phases of the building life cycle (section 6.2.3.3).

#### 6.2.3.2 Data scope

Early proposals which data should be covered by a BP already show significant similarities with more recent findings. Examples can be found in the report of the German Parliament (section E.1.1) and in the official proposals for a building passport (section E.1.2) and a housing file (section E.1.3).

Within more recent studies, examples can be found for all categories of raw building-related data that should be covered in DBPs/DBLs. Several publications suggest the inclusion of general data, such as information about the involved actors, the ownership, the building type or the unambiguous identification of a building and its components (Malinovec Puček et al., 2023a, p. 15; Rohde et al., 2011, p. 73). Furthermore, DBPs/DBLs should include information about the physical structure and its characteristics in the form of geometric data (Malinovec Puček et al., 2023a, p. 9), a material inventory (Dourlens-Quaranta et al., 2020, p. 31; Hartenberger et al., 2021, p. 25), or functional characteristics such as the buildings' accessibility (Malinovec Puček et al., 2023a, p. 9). In addition, legal data, for example in the form of insurance or taxation information (Dourlens-Quaranta et al., 2020, p. 31), process data such as maintenance records (Malinovec Puček et al., 2023a, p. 9), and performance data are supposed to be included in a DBP/DBL.

The data content of BPs and DBLs exceeds single data and reaches to aggregated indicators, important documents, and even complete tools. Indicators build upon the availability of single data and mostly include some form of assessment. The literature describes several performance characteristics and partly names the indicators that can be used for that:

- Energy performance and efficiency: Energy efficiency classes (Malinovec Puček et al., 2023a, p. 9)
- Environmental performance: LCA results, GWP (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 2; Malinovec Puček et al., 2023a, p. 9)
- Overall sustainability: EU level(s) indicators (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 3)
- Renovation potential (Dourlens-Quaranta et al., 2020, p. 31)
- Smart readiness and digitalization status: Smart readiness indicators (Dourlens-Quaranta et al., 2020, p. 31; Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 10)
- Financial performance (Hartenberger et al., 2021, p. 24)
- Social performance (Hartenberger et al., 2021, p. 24)

Relevant documents that are frequently mentioned in the literature are EPCs, additional ratings, and certificates, building permits, design documents, insurance documents, contracts or maintenance records (Dourlens-Quaranta et al., 2020, p. 31; Gómez-Gil et al., 2023, p. 3; Malinovec Puček et al., 2023a, pp. 2–18). Other tools to be included in BPs and DBLs according to the literature are digital product passports (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 7), predictive maintenance plans (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, p. 10), material passports (Malinovec Puček et al., 2023a, p. 9), digital twins, and renovations roadmaps (Buchholz & Lützkendorf, 2022a, p. 7).

There are first proposals how to integrate the scope of data in a data model. One of them originates from the most recent research by the EC, and the data categories proposed are shown in section E.1.8. These data categories form the basis for a LD-based semantic data model.

While being not at the forefront of investigations, the literature also deals with requirements on the quality of data. DBPs/DBLs should ensure the accuracy, availability, and consistency of data (Buchholz & Lützkendorf, 2022a, p. 4; Gómez-Gil, López-Mesa, & Espinosa-Fernández, 2022, p. 67). Above that, several publications stress the importance of data interoperability through appropriate interchangeable formats (Gómez-Gil et al., 2023, p. 3) and the need for data security and protection (Buchholz & Lützkendorf, 2022a, p. 4). Ensuring data security goes along with the pursuit of trustworthiness and the compliance with data privacy regulations (Dourlens-Quaranta et al., 2020, p. 34). In addition, the possibility to trace back data should be given (Mêda Magalhães et al., 2022, p. 5). The EC (2023, p. 38) promotes the application of the FAIR principles to ensure data quality with a special emphasis on interoperability. Platform CB'23 (2022, p. 43) explores alternative data ownership models within data storage paradigms for DBPs/DBLs, an issue where no clear consensus exists. It advocates a hybrid model that combines centralized oversight for data quality and public access with decentralized management of sensitive information.

#### 6.2.3.3 Addressees, life cycle coverage, and use cases

DBPs/DBLs, based on their broad functionality for information management, address a wide variety of actors within the real estate industry including building owners, building users, real estate managers, all kinds of service providers, and public authorities, as described, for example in Volt et al. (2020, p. 14). However, there is hardly evidence on how the diverging requirements of different users and their levels of expertise should be addressed in DBPs/DBLs. While this might be slightly less relevant for stakeholders, it is even more for different types of building owners, such as owner-occupiers of residential buildings and professional housing companies.

More evidence exists for building use types that should be covered. According to Malinovec Puček et al. (2023a, p. 8), DBPs/DBLs should be applicable to the entire building stock including residential and non-residential buildings. Toth et al. (2021) suggest the development of a suitable typology for building use types that distinguishes between new and existing buildings. This is, at least partially, contradictory to applying the tool to the entire life cycle, as laid out later in this section. Based on the requirement to apply DBPs/DBLs to all building use types, they necessarily need to address different types of building owners.

The literature considers single buildings as the main object of assessment, but this aspect is not always made clear. Sometimes also the surrounding area of a property is taken into account as well (Rohde et al., 2011, p. 72). Dejaco et al. (2017, p. 185) go one step further by distinguishing between a logbook on the building level and a logbook on the district level that can work together by sharing data between each other and by taking over functions for the respective level. Mêda Magalhães et al. (2022) mention the possibility to make observations on the city scale by aggregating data from the building level.

There is strong evidence that DBPs/DBLs should cover the whole life cycle of a building. On the one hand, this is proposed in main definitions such as the one from Hartenberger et al. (2021, p. 14). On the other hand, several publications state the relevance of the concept in at least two out of four life cycle stages (Hartenberger et al., 2021, p. 14; Malinovec Puček et al., 2023a, p. 8; Mêda Magalhães et al., 2022, p. 3). The EC (2023, p. 11) connects occasions throughout the life cycle with typical data categories (Figure 6.7).

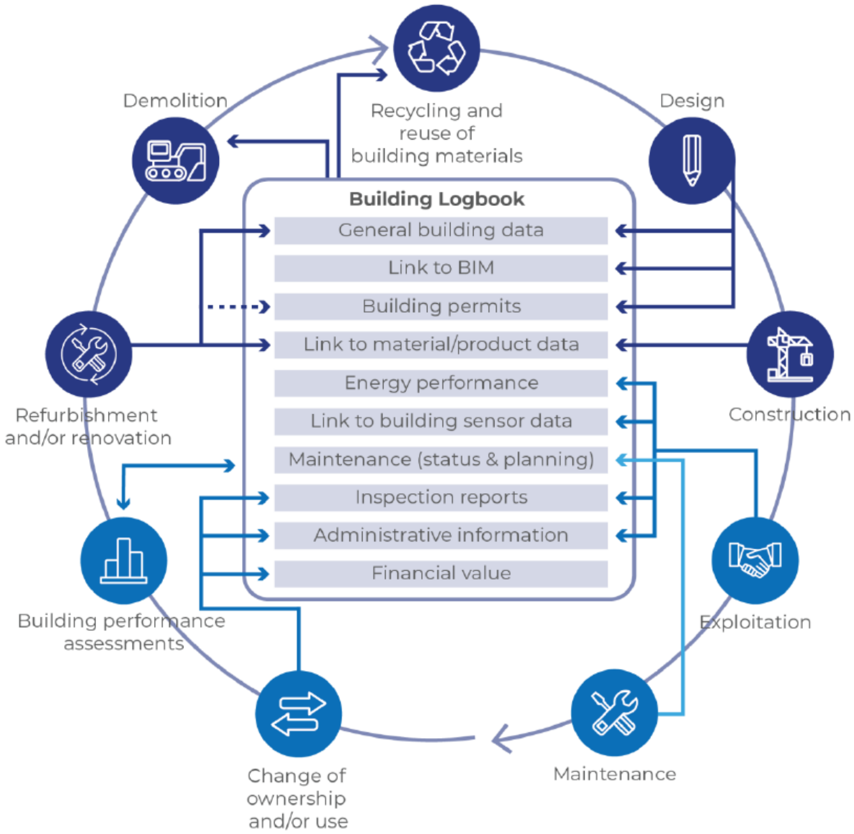



Figure 6.7: Life cycle coverage of digital building logbooks in connection with relevant data categories (EC, 2023, p. 11)

Another approach to determining the life cycle scope of these tools is by examining the specific task areas they address. Although the literature does not offer a comprehensive overview, it does highlight numerous task areas relevant to the real estate industry. This includes:

- Facility and building management including maintenance planning and execution (Dejaco et al., 2017, p. 188; Dourlens-Quaranta et al., 2020, p. 30; Hartenberger et al., 2021, p. 15; Signorini et al., 2021, p. 4)
- Valuation (Dourlens-Quaranta et al., 2020, p. 30; German Parliament, 1998, p. 181; Hartenberger et al., 2021, p. 19)
- Risk management (Dejaco et al., 2017, p. 185; Malinovec Puček et al., 2023a, p. 2)
- Tasks concerning the public sector, for example, lawmaking, funding program providing or verifying compliance with building regulations (Hartenberger et al., 2021, p. 19)

Recent projects, such as openDBL (2024b) determine more use cases in the early life cycle stages including data collection, sharing, and analytics throughout development, design, and construction. This approach expands the perception of the functionality of DBPs/DBLs compared to earlier studies.

#### 6.2.3.4 Technical implementation

The literature on DBPs/DBLs lists several ICTs that are already relevant today and some that might be relevant in the future. All of these technologies aim to fulfill a specific function in information management by, among other things, supporting actors in data collection, data storing, data analysis, or security management. A severe number of publications considers virtual building models under the use of BIM and digital twins as highly relevant. Mêda Magalhães et al. (2022, p. 6) basically suggest to merge DBLs and digital twins to ensure a continuous updating and assurance of building-related information. Gómez-Gil, Espinosa-Fernández, and López-Mesa (2022, p. 11) suggest to combine several technologies in order to create leverage and synergy effects. In particular, they highlight the possibilities for data collection through LIDAR 3D scanning, the advantages of combining sensor technology, IoT, and AI for monitoring reasons, and the creation of digital twins based on BIM, sensor data and, IoT applications (Gómez-Gil, Espinosa-Fernández, & López-Mesa, 2022, pp. 6–7).

A thorough perspective on technical aspects can be found in the study "Technical guidelines for digital building logbooks" which was part of the second line of research on the topic by the EC. Among other things, the study emphasizes on the following aspects:

- Cloud computing and scalable infrastructure with three-tier architecture (front-end, back-end, database)
- Linked data technology and ontologies for semantic interoperability
- Open data formats (e.g., JSON, JSON-LD) for data sharing
- Data security technologies including encryption, authentication, and authorization mechanisms
- Visualization and analytics tools for user-friendly data interaction
- Platform scalability technologies (e.g., modular design, containerization) for adaptability to future needs (EC, 2023, pp. 52–72).

Current European research initiatives further explore potentials of ICTs, including blockchain technology (Buildchain, 2024), AI-based analytics (Digibuild, 2022), and various data formats (Katsifaraki et al., 2024, pp. 161–166).

#### 6.2.3.5 Barriers for implementation

DBPs/DBLs encounter several key challenges and barriers, which might have prevented a higher distribution and more success in the industry. So far, many proposals, at least those from the literature, are still in a conceptional stage and were not implemented in practice. Table 6.2 lists frequently mentioned barriers in the literature.

Table 6.2: Barriers for the implementation of digital building passports and logbooks based on Buchholz and Lützkendorf (2023, p. 909), EC (2023, pp. 28–30), and Dourlens-Quaranta et al. (2020, p. 8)

| Type of barrier | Relevant aspects |
|---|---|
| Legal | Potential data security and privacy safety issues, unclear responsibilities |
| Economic | High initial costs, administrative burden, low incentives for data sharing, lack of sound business models |
| Technical | Data storage management, integration with legacy systems |
| Data quality | Data availability, accuracy, and interoperability |

| | |
|---|---|
| Actor-related | Lack of trust, motivation, digital expertise, knowledge about functionality of the tool |

Several of these issues can be addressed through the functionality attributed to DBPs/DBLs in the literature, while others still require solutions. The aspects mentioned will be revisited in the context of proposals for a LC-BIS later in this thesis.

#### 6.2.3.6 Summary and fact sheet

The most important findings on DBPs/DBLs were summarized in the following fact sheet (Table 6.3). It demonstrates that these tools hold significant potential to function as LC-BISs. Although various drivers have increased attention toward DBPs/DBLs, their conceptual evolution has gradually aligned with the definition of LC-BISs, and despite some gaps in the literature, the core concept, from primary functions to data scope and life cycle coverage, fits well with the LC-BIS requirement profile.

Table 6.3: Fact sheet on digital building passports and logbooks

| **Term(s)** | **(Digital) building passport, digital building logbook, electronic building passport housing file** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Goals** | Comprehensively store and manage building-related data throughout the life cycle of a building, make it available to different actors when needed, and thus offer potentials to drawing insights through analyzing and using data | | | | | | | |
| **Background and drivers** | Concept and idea already exist for several decades, but have not found wide adoption in the real estate industry; new approaches focus on integration of suitable technologies to make use of digitalization and automation; increasing demand in different domains of the real estate industry, based on information management issues, such as lack of transparency, poor information quality, poor data sharing | | | | | | | |
| **Main functions** | ☒ | Data and document repository | ☒ | Data sharing platform | ☐ | Digital copy | ☐ | Action plan and guide |
| | ☒ | Data creation and collection aid | ☒ | Quality management system | ☐ | Assessment tool | ☐ | Other: |
| **Life cycle stages** | ☒ | Development | ☒ | Construction | ☒ | Use | ☒ | End-of-life |
| **Data categories** | ☒ | Master data | ☒ | Inventory data | ☒ | Legal and economic data | ☒ | Performance data |
| **Suitability as LC-BIS** | Very high, since many typical issues in information management can be addressed | | | | | | | |

# 6.3 Topical passport schemes

This section examines passport schemes that are more specialized than DBPs/DBLs, including material passports (section 6.3.1), renovation passports (section 6.3.2), and digital product passports (section 6.3.3). The level of detail in each subsection is guided by the density of evidence in the literature concerning aspects relevant to LC-BIS requirements. The analysis focuses on evaluating the functionality of these tools based on the specifications of the requirement profile.

## 6.3.1 Material passports

### 6.3.1.1 Objectives and functions

Material passports are not universally defined, but it is clear that the concept focuses on the built-in materials of a building. This group of tools receive increasing intentions by researchers and practitioners based on their intended application to improve circularity in the built environment. Different terms, such as material inventory (Schiller et al., 2022, p. 80), building material information system (Reisinger et al., 2014, p. 80), product passport (van Capelleveen et al., 2023, p. 1), circularity passport (M. Heinrich & Lang, 2019, p. 2), or material database (Oberti & Paoletti, 2020, p. 86) have been introduced in the past, partly with the goal to overcome existing misconceptions. The literature more or less agrees on a couple of core objectives and functions of material passports including:

- Keep better track of materials, elements, and components installed in buildings throughout their lifespan and thus reserve or increase their value (M. Heinrich & Lang, 2019, p. 5).
- provide information about the characteristics of building materials, elements, and components.
- Support decision-making regarding the choice, maintenance and disposal of building materials in the design, operation, and deconstruction of buildings (M. Heinrich & Lang, 2019, p. 5).
- Improve the recovery, reuse, and recycling potential of construction products through appropriate measures and assessments (Göswein et al., 2022, p. 3).
- Improve the health of occupants through early identification of potential pollutants (Reisinger et al., 2014, p. 98)
- Promote waste minimization, resource efficiency, and circularity (Göswein et al., 2022, p. 3; Luscuere, 2017, p. 26).

Two interpretations dominate the discussion concerning the main function of material passports: Some interpret it as a data object or document that contains information referring to one specific building component, element, or material. In this sense, the terms product passport or resource passport are used similarly. Others rather see a material passport as a data repository for material-related information regarding a building. Here, terms like material inventory or material information system might be better suited. This difference in interpretation is partly addressed by the literature that shows opportunities to consider information on building materials on different hierarchy levels. Panza et al. (2022, p. 1491) made suggestions on how to share material passports in a platform environment and aggregate the respective information for a more holistic view.

There is also research on how material-related information can be illustrated on a cadastral level that enables analyzes for large building stocks (Schiller et al., 2022, p. 172).

In addition to functioning as repositories for building material data, the literature also assigns these systems an evaluative role, specifically, in assessing the circularity potential of buildings and their components. For example, Honic et al. (2019b, pp. 5–7) propose incorporating a disposal indicator to evaluate the recycling potential of building elements.

#### 6.3.1.2 Data scope

According to the literature, a material passport should contain general data, such as the address of the building, a passport ID (Göswein et al., 2022, p. 6), and material- and product-specific information, such as unique product identifiers, used data sources, or manufacturer information (Göswein et al., 2022, p. 6; M. Heinrich & Lang, 2019, p. 16). The core data of a material passport are building component and material properties. These data are supposed to be collected throughout design and construction as well as updated and enhanced throughout the life cycle. This sets the basis to determine volumes, quantities, and qualities of built-in materials on a building level (M. Heinrich & Lang, 2019, p. 10; Reisinger et al., 2014, p. 80). In the European context, this information is increasingly represented by the "bill of materials" and "bill of quantities", as laid out in the European sustainability assessment framework "Level(s)" (EC, 2021). Important contextual information concerns the geometric location of building components and materials in a building (Munaro et al., 2019, p. 4). Additional metadata can include the timing of installation.

Several publications mention the relevance of including LCA results regarding a building component or material, such as the Global Warming Potential (GWP), the Acidity Potential (AP) or the Primary Energy Intensity (PEI) (M. Heinrich & Lang, 2019, p. 9; Honic et al., 2019b, p. 5; Munaro et al., 2019, p. 4). These data, that can be derived from EPDs, for example, are essential for LCAs on a building level. Additional to environmental assessments, economic, and social assessments can be considered too (M. Heinrich & Lang, 2019, p. 9).

#### 6.3.1.3 Use cases

Material- and product-based information are important for a variety of tasks throughout the life cycle of buildings. They have the potential to significantly contribute to sustainability assessments including LCAs, sustainability reporting, or risk assessments. One use case can lie in the detection and assessment of materials of concern and harmful substances. In the upstream value chain, material passports are assumed to support construction product manufacturers in developing resource-extensive products that are harmless to health and show a high recycling potential, among other things (M. Heinrich & Lang, 2019, p. 5; Panza et al., 2022, p. 1491). Building designers, developers, and constructors could potentially use material passports in choosing suitable building components and materials while facility managers could be provided with insights and guidance for maintenance management (Göswein et al., 2022, p. 3; M. Heinrich & Lang, 2019, p. 5). This can pave the way towards predictive maintenance approaches. An important use case concerns the end of the life cycle, where material-related information could help to plan the deconstruction of buildings and the disposal or recycling process (M. Heinrich & Lang, 2019, p. 5).

A frequently elaborated aspect in the literature includes the integration of material passports with BIM (Honic et al., 2019a, pp. 222–227; Leindecker et al., 2025, p. 526; Reisinger et al., 2014, p. 108). BIM can facilitate the localization of building materials and components in a virtual building model and also significantly contribute to the digitization of workflows.

#### 6.3.1.4 Current approaches including building resource passports

A current approach focused on building materials in the industry is presented by the German Sustainable Building Council (DGNB) (2023b) that reacts to the intention of the German government of introducing a building resource passport. The idea has been formally introduced as part of the coalition agreement of the German government (Sozialdemokratische Partei Deutschlands [SPD] et al., 2022, p. 71). However, no specifications were made about the functionality of such a tool. The DGNB (2023b) tried to fill this space by developing its own version of a building resource passport. According to the proposal, a building resource passport is a document that contains aggregated information and characteristics about the materials used in a building as well as respective indicators concerning their dismantling and recycling potential (Propach et al., 2023, p. 354). For further details, please refer to the example in section E.2.1. The passport should be created during the construction stage and passed on to the building owner, so that the information is available during the use stage (DGNB, 2023b).

In Germany, there is also ongoing work on a standard for building resource passports commissioned by the government itself. At the moment, it is intended to define four categories a building resource passport should cover including:

- Building material and product inventory with detailed information on physical properties and manufacturer information
- Estimation of primary raw materials used on a building level
- Assessment of the circularity potential
- Information on potentially harmful substances (source: personal communication with a commissioned researcher)

Ideally, a building resource passport would extend beyond merely tracking material flows to also encompass other resource flows, such as emissions, water usage, and information. However, the prevailing interpretation still aligns it closely with the concept of a material passport.

On a broader scale, the materiality of buildings in the context of circular economy is subject of international standardization. The working group 4 of the European standardization committee CEN/TC 350/SC 1, for example, is explicitly working on the standardization of circular related information in construction works with requirements on digital passports as part of their work.

#### 6.3.1.5 Summary and fact sheet

In comparison to DBPs/DBLs, material passports are more specific tools. On the one hand, they share similarities in life cycle coverage and serve as data repositories; on the other hand, their focus is narrowly confined to building materials, which limits their suitability as LC-BISs (Table 6.4). Nevertheless, material passports can still play an important role in building-related information management, particularly when the distinctive aspects of their standalone functionality, centered specifically on building materials, are clearly defined and recognized. For further information on how different BISs interact, please refer to section 6.6.

Table 6.4: Fact sheet on material passports

| **Term(s)** | **Material passport, material inventory, resource passport, product passport, circularity passport, building material information system** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Goals** | Store and manage data about the built-in materials in a building throughout its life cycle; provide the basis for material-related evaluations | | | | | | | |
| **Background and driver** | Lack of availability and overall quality of building material- and product related data | | | | | | | |
| **Main functions** | ☒ | Data and document repository | ☐ | Data sharing platform | ☐ | Digital copy | ☐ | Action plan and guide |
| | ☒ | Data creation and collection aid | ☐ | Quality management system | ☒ | Assessment tool | ☐ | Other: |
| **Life cycle stages** | ☐ | Development | ☐ | Construction | ☐ | Use | ☒ | End-of-life |
| **Data categories** | ☒ | Master data | ☒ | Inventory data | ☐ | Legal and economic data | ☒ | Performance data |
| **Suitability as LC-BIS** | Good in terms of keeping track of material-related information; limited suitability as LC-BIS | | | | | | | |

## 6.3.2 Renovation passports

Actors of the real estate industry require instruments and tools to support their decisions on energy renovations. One instrument that has been established over the years by regulation are EPCs. However, they often show different maturity levels and implementation states across different countries and they lack to support decision-making (Fabbri et al., 2016, pp. 4–5). Therefore, the EC announced the proposal of another instrument in the revised version of the EPBD (EC, 2018, Art 19 a) called *building renovation passports* (BRPs) that should provide more proficient advise in the long-term. The objective is to foster more energy renovations in the building stock in order to improve the energy efficiency and thus to contribute to climate change mitigation targets (Fabbri et al., 2016, p. 4; Libórîo et al., 2018, p. 6). Several aspects that are responsible for the insufficient rate of energy renovations were identified as drivers for BRPs: The Green Finance Institute (2021a, p. 4) states that there is a lack of information regarding suitable energy efficiency measures as well as the available financing options. Espinoza-Zambrano et al. (2023) mention information gaps and information asymmetries responsible for the inefficient decision-making process.

The literature uses different terms with a similar meaning to describe the concept, including "building renovation passport" (Fabbri et al., 2016, p. 1; Green Finance Institute, 2021a, p. 4), "individual (building) renovation roadmap" (Fabbri et al., 2016, p. 5; Libórîo et al., 2018, p. 6) or "scheduled renovation roadmap" (Espinoza-Zambrano et al., 2023). A renovation roadmap aims to provide guidance for building owners and stakeholders involved in energy renovations by setting out a step-by-step action plan for a specific building (Fabbri et al., 2016, p. 6). For this, several publications identify guiding principles that should be taken into account in the development of BRPs. On the one hand, the timing and sequencing of actions should be defined for a long-term perspective. On the other hand, the roadmap should incentivize and motivate building owners to invest in the energetic quality of their buildings. In addition, the instrument should incorporate some form of automation (Fabbri et al., 2016, p. 37; Sesana & Salvalai, 2018, p. 204; Sousa Monteiro et al., 2018, p. 10).

The analysis of the identified literature reveals several common characteristics between BRPs and DBPs/DBLs. The reason for this lies in the high information demand in planning and conducting energy renovations. Thus, a BRP is often assumed to either include or cooperate closely with a building logbook that functions as a data repository and provides all the information necessary for building renovations (Fabbri, 2017, p. 1411; Libórîo et al., 2018, p. 7). In fact, the results of the EU-based research on BRP were one of the main initiators to investigate DBPs/DBLs more closely (section 6.2.1). Due to this connection, the building logbooks described as part of BRPs also show a similar scope and profile than DBPs/DBLs. Among other things, BRPs:

- function as a data and document collection that is accessible for the relevant actors in energy renovations. Above that, specific assessments can be made that lead to the recommendation of the renovation roadmap.
- regard buildings as the main object of consideration. In addition, the possibility of conducting surveys on a building stock level are mentioned especially for tasks of the public sector.
- are beneficial for many task areas and the respective actors in the real estate industry.
- cover a wide range of building-related data. The focus lies on data that are relevant in planning and executing energy renovations (Green Finance Institute, 2021b; Libórîo et al., 2018, p. 15).

A difference can be identified in the predominant focus on the use stage and on existing buildings in BRPs.

A practical implementation of renovation roadmaps can be found in Germany through the "Individueller Sanierungsfahrplan" (iSFP). It is an instrument of energy consulting, primarily designed to support private homeowners in identifying suitable energy efficiency measures for their buildings. The iSFP is based on an on-site assessment by qualified energy consultants and results in a structured, step-by-step renovation plan. It not only provides tailored recommendations but is also officially recognized as proof for eligibility for certain public funding schemes (e.g., "Bundesförderung für effiziente Gebäude" [BEG] subsidies) (Bundesamt für Wirtschaft und Ausfuhrkontrolle [BAFA], 2024; Gebäudeforum Klimaneutral, 2025a). However, the iSFP remains a static document and, as such, does not fulfil the dynamic and data-integrated functions associated with building renovation passports.

Beyond individual consulting, there is a growing market for software solutions targeted at housing associations and real estate companies that aim to generate renovation roadmaps or decarbonization paths on a larger scale. These solutions are often framed as climate strategies and reflect the increasing relevance of digital planning instruments for strategic portfolio management (section 6.5.2.3 Tools for sustainability assessment and management).

Table 6.5 contains a summary of findings on BRPs in a fact sheet to assess their suitability as LC-BIS.

Table 6.5: Fact sheet on renovation passports

<table>
<tr><th>Term(s)</th><th colspan="8">Building renovation passport, renovation roadmap, decarbonization roadmap, climate roadmap</th></tr>
<tr><td>Goals</td><td colspan="8">Collecting and managing building-related data that are necessary for making profound renovation decisions in the long term</td></tr>
<tr><td>Background and drivers</td><td colspan="8">Current understanding as the result of the efforts from the EC to develop tools that facilitate increased energy renovation activity in the EU; closely connected to EPCs and other tools for assessing the energetic quality of a building;</td></tr>
<tr><td rowspan="2">Main functions</td><td>☒</td><td>Data and document repository</td><td>☐</td><td>Data sharing platform</td><td>☐</td><td>Digital copy</td><td>☒</td><td>Action plan and guide</td></tr>
<tr><td>☒</td><td>Data creation and collection aid</td><td>☐</td><td>Quality management system</td><td>☐</td><td>Assessment tool</td><td>☐</td><td>Other:</td></tr>
<tr><td>Life cycle stages</td><td>☐</td><td>Development</td><td>☐</td><td>Construction</td><td>☐</td><td>Use</td><td>☒</td><td>End-of-life</td></tr>
<tr><td>Data categories</td><td>☒</td><td>Master data</td><td>☒</td><td>Inventory data</td><td>☐</td><td>Legal and economic data</td><td>☒</td><td>Performance data</td></tr>
<tr><td>Suitability as LC-BIS</td><td colspan="8">Limited suitability, when only used in the context of a roadmap; synergies and job-sharing with LC-BISs possible</td></tr>
</table>

While BRPs show limited suitability as a standalone LC-BIS due to their specific scope, they can be a valuable addition for managing renovation-specific data.

### 6.3.3 Digital product passports

A digital product passport (DPP) is a sector-agnostic instrument to provide product-related information throughout the whole product life cycle. The concept found attention through the EC, which will make DPPs a mandatory instrument from 2026 onwards, starting with pivotal industries. The construction industry is one of them, while DPPs were also formally introduced in the latest Ecodesign for Sustainable Products Regulation (ESPR), 2024. Specifications of requirements are expected for 2025.

Before it became a policy instrument, several studies dealt with DPPs. According to Adisorn et al. (2021, p. 2), a DPP should provide data on the origin, composition, repair, and dismantling options for a product. Thus, it aims to bridge information gaps throughout the life cycle of a product buy providing data to stakeholders when needed. Götz et al. (2022, p. 8) state that DPPs should contain a minimum of information that could be determined as mandatory by regulations. In addition, data should be updateable, stored in an interoperable format, and trustworthy. Several benefits are connected to DPPs:

- Standardization and digitization of product information
- Opportunity for new business models for product manufacturers based on better data availability and quality
- Facilitation of compliance checking for products by market surveillance authorities
- Improved customer-orientation by retailers
- More transparency for users and thus more conscious purchasing decisions
- Improved waste management through deconstruction information, material composition, etc. (Adisorn et al., 2021, pp. 9–11; Götz et al., 2022, p. 8)

The literature addresses open questions for the design of DPPs, referring to the product groups to be included, the application level (level of detail for the object of consideration), and solutions for data storages, data carriers, and data accessibility (World Business Council for Sustainable Development [WBCSD] & Boston Consulting Group [BCG], 2023, pp. 5–7). While it is evident that DPPs might be applicable to specific construction products, it remains open whether whole buildings can be considered in a DPP. At present, it seems unlikely that a complex product such as a building can be considered in a common framework for all products.

Plociennik et al. (2022, p. 124) pick up the idea of DPPs and suggest a digital lifecycle passport that takes in similar functions as a DPP, but aims to be updated more dynamically. By proposing the use of a cloud infrastructure, the authors stress the importance of accessing and updating data seamlessly by included actors (Plociennik et al., 2022, p. 124).

DPPs are not suited as LC-BISs, since the object under consideration is different. For this reason, no fact sheet is provided. However, the flawless integration of information from DPPs into LC-BISs will be an important task in the future.

## 6.4 Virtual building models

Within this section, the potential of tools based on virtual building models for functioning as LC-BIS is evaluated. Prior to discussing their strengths and limitations (section 6.4.2), a brief overview of their functionality and current trends is provided (section 6.4.1). These points are drawn from a more detailed explanation of the fundamentals and trends presented in the appendix (section E.3), ensuring that the main text remains focused on the essential aspects.

### 6.4.1 Functionality and current trends

Virtual building models, namely BIM models and digital twins, offer significant potential to enhance information management throughout the building life cycle based on the findings of the literature review. BIM and digital twins are closely interrelated and increasingly converge in scope and functionality, which is why they are jointly considered under the umbrella of virtual building models when evaluating their suitability for LC-BISs. BIM has evolved from basic 2D/3D representations to multidimensional models that integrate time, cost, facility management, and sustainability aspects, while digital twins build on these foundations to enable real-time monitoring, simulation, and predictive analytics. Theoretical and empirical studies indicate that leveraging these tools can improve decision-making and operational efficiency across all stages of a building's existence. Table 6.6 provides an overview of current trends in virtual building models, with brief descriptions of each trend.

Table 6.6: Overview on current trends in applying virtual building models to information management throughout the building life cycle (section E.3.2)

| Trend | Short Description |
|---|---|
| N-dimensional BIM and BIM Level Evolution | Expands basic 3D models by adding dimensions (e.g., 4D time, 5D cost, 6D facility management, 7D sustainability), thereby enriching the informational depth. |
| Building Lifecycle Management (BLM) | Extends BIM applications to support all building phases, from design through construction to deconstruction, ensuring continuous, up-to-date information. |
| Collaborative BIM | Integrates multi-stakeholder workflows within shared BIM environments, streamlining data exchange and coordination. |
| BIM for facility management and As-built BIM | Transitions design models into dynamic as-built models that support facility management through updated, operational data. |
| BIM for deconstruction | Applies BIM at the end-of-life stage to plan, simulate, and optimize deconstruction processes, facilitating recycling and waste reduction. |
| Common Data Environments (CDEs) | Employs centralized or federated platforms for storing, managing, and sharing building data, ensuring consistency and accessibility across the life cycle. |
| Digital Twins | Extend BIM by integrating real-time sensor data and enabling dynamic interaction between physical and digital environments, supporting monitoring, simulation, and optimization across the building life cycle. |

The selected trends highlight the role of virtual building models in supporting information management processes across the building life cycle but do not capture all current developments within this scope. In particular, a range of more technical trends aim to enhance the functionality and usability of such models. These include, for example, the integration with IoT systems for real-time data acquisition (Siccardi & Villa, 2023, p. 3), the use of linked data and semantic web technologies to improve data interoperability and structuring (Pauwels et al., 2017, p. 161), and the application of blockchain to support traceability and data ownership management (Tavakoli et al., 2024, p. 4).

For a more detailed discussion of fundamentals of BIM and digital twins as well as respective trends, please refer to section E.3.

## 6.4.2 Evaluation of suitability for information management

### 6.4.2.1 Strengths

The rational for interpreting virtual building models as LC-BISs is indicated clearly within the literature, which interprets them as "life cycle platform" (Sacks et al., 2018, p. 19) or "data repository" (Gu & London, 2010, p. 988). These models are designed to centralize and manage building-related data across all life cycle stages, aligning closely with the concept of BLM, which emphasizes the integration of digital models and semantic information to support long-term building operation and decision-making (section E.3.2).

A key strength lies in their ability to digitally visualize building geometry, enabling a detailed and precise representation from design to demolition. This supports planning, understanding, and communication across life cycle actors (Borrmann, König, et al., 2018b, p. 7). In addition, as elaborated in the trends section (section E.3.2), these models have evolved beyond static representations and are increasingly capable of incorporating additional data dimensions (e.g., time, cost, sustainability), which enhances their value for holistic information management.

BIM and digital twins also support advanced data analytics, enabling simulations, scenario analyses, performance assessments, and predictive modeling (section E.3.3). These functions facilitate informed, data-driven decision-making and allow stakeholders to optimize performance, anticipate maintenance needs, and improve resource efficiency.

Another core advantage is their support for integrated digital workflows. As discussed in the context of collaborative BIM (section E.3.2), virtual building models enable real-time coordination across disciplines by replacing fragmented, tool-specific processes. The use of CDEs further strengthens this capacity by providing a structured, traceable environment for managing and exchanging project information throughout the building life cycle. This integration reduces redundancies, minimizes information loss, and improves consistency across stages and actors.

The use of standardized data formats, particularly IFC, reinforces the interoperability of virtual building models. These modular and extensible structures allow for integration with a variety of data sources and platforms, supporting consistent information practices across organizations. However, strict formalization requirements can also pose challenges to flexibility and adaptability in dynamic project settings (Costin et al., 2022, pp. 23–24).

The continued development of BIM and digital twin technologies reflects their long-term relevance for life cycle information management. Research is increasingly directed at their application in areas such as sustainability, automation, and real-time monitoring, which broadens their role beyond initial planning and construction. This adaptability further supports their suitability as LC-BISs.

A current example that illustrates this evolving potential is the iECO project within Gaia-X, a European initiative aimed at building sovereign digital infrastructures. iECO seeks to create a cross-organizational data ecosystem for the construction industry, based on tamper-proof digital twins embedded in secure data spaces, enabling collaboration, smart services, and data control across the life cycle (iECO, 2022).

#### 6.4.2.2 Barriers and limitations

While offering substantial benefits across the life cycle, several intrinsic barriers limit the suitability of BIM and digital twins as LC-BISs. One critical limitation lies in their strong focus on specific life cycle stages, particularly design and construction, and on geometric data. As outlined in section E.3.2, the early development of BIM centered around 3D modeling and visual representation, which, while effective for design coordination, offers limited value for tasks in later stages such as facility management or deconstruction. In these phases, actors primarily require alphanumeric information, such as performance indicators, energy consumption data, or cost and maintenance records, which, while technically integrable into BIM environments, are not consistently supported in practice due to missing conventions, inadequate data modeling standards, or limited alignment with user needs.

Another major barrier is the complexity of the systems. BIM and digital twins often rely on specialized tools and data formats, requiring expertise that many life cycle actors, particularly facility managers, building owners, or small firms do not possess. As described in the context of collaborative BIM (section E.3.2), effective implementation presumes structured coordination, clearly defined roles, and governance mechanisms, all of which increase the entry threshold.

Interoperability and data quality remain persistent issues. As seen with CDEs (section E.3.2), achieving seamless information exchange across platforms and life cycle phases is difficult due to inconsistent standards, non-integrated systems, and a lack of consistent semantic structure. Poor interoperability impedes the continuous use of data, and high data quality expectations often lead to additional burdens for those responsible for inputting or updating information. While approaches based on linked data or semantic web technologies offer promising solutions, their adoption is still limited in practice.

Economic factors also play a significant role. The implementation of BIM and digital twin systems involves substantial upfront investments in software, training, and data modeling. As found for the use of BIM in facility management (section E.3.2), cost-related concerns are amplified by the fact that long-term benefits, such as operational efficiency or improved decision-making, are often hard to quantify and remain abstract for many actors. This cost-benefit uncertainty is particularly critical for actors with limited budgets or for projects without a strong digitalization mandate.

In addition to these life cycle-specific limitations, broader barriers to the adoption of virtual building models are widely discussed in the literature. These include technological, cultural, organizational, and legal challenges that apply across different actor groups and project types. Table 6.7 summarizes these challenges.

Table 6.7: Barriers for the use of virtual building models for information management based on Enshassi et al. (2019, pp. 190–192) and Lill and Witt (2019, p. 301)

| Barrier Type | Description |
|---|---|
| Technological | Limited interoperability between tools; insufficient alignment with data needs beyond geometry. |
| Economic | High costs for implementation, training, and updates; unclear return on investment for lifecycle applications. |
| Cultural and workflow | Resistance to changing established practices and workflows, especially for non-construction-focused actors. |
| Human resource | Lack of expertise among actors not directly involved in design and construction phases. |
| Data governance | Unclear ownership, sharing rights, and liability related to data, discouraging collaboration. |
| Complexity | High technical demands make BIM and digital twins unsuitable for widespread use by non-experts. |

In practice, barriers to implementing BIM and digital twins are highly actor-dependent and often shaped by specific project contexts, organizational structures, and regulatory environments. While some actors may overcome these limitations through targeted investments and capacity building, others, particularly smaller firms, may struggle to adopt such systems meaningfully without broader support structures.

#### 6.4.2.3 Summary and fact sheet

The literature review confirms that virtual building models have high potential for life cycle information management. Their technical and functional capacities are sufficient for LC-BIS applications. The challenge lies in determining which user groups can effectively utilize these models. In practice, a major drawback is that BIM and digital twin applications require specialized expertise that is not yet widespread among practitioners, a finding also highlighted in interviews with real estate industry experts. Additionally, a significant barrier is the gap between the high level of data structuring demanded by virtual building models and the lower level of data organization currently prevalent in the industry (Table 6.8).

Table 6.8: Fact sheet on virtual building models

| **Term(s)** | **Virtual building model, digital building model, BIM tool, BIM platform, BIM software, BIM application, digital twin, digital twin platform** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Goals** | Fostering BIM as the method and paradigm to digitize the process of design, construction, and operation of buildings throughout their life cycle | | | | | | | |
| **Background and drivers** | Digitization of geometric modeling of buildings and related workflows throughout the life cycle of a building; new possibilities to improve workflows and decision-making based on using data in virtual building models which are rich in information | | | | | | | |
| **Main functions** | ☒ | Data and document repository | ☒ | Data sharing platform | ☒ | Digital copy | ☐ | Action plan and guide |
| | ☒ | Data creation and collection aid | ☒ | Quality management system | ☒ | Assessment tool | ☐ | Other: |
| **Life cycle stages** | ☒ | Development | ☒ | Construction | ☒ | Use | ☒ | End-of-life |
| **Data categories** | ☒ | Master data | ☒ | Inventory data | ☒ | Legal and economic data | ☒ | Performance data |
| **Suitability as LC-BIS** | Very high suitability, when building-related data and respective processes are fully digitized; limited suitability for unstructured and heterogenous data, as well as for non-expert users | | | | | | | |

It is important to note that the capabilities outlined in the fact sheet do not pertain to any single BIM or digital twin application, but rather illustrate the full potential of this group of BISs. Ultimately, while virtual building models are highly suitable as LC-BIS, they are not yet applicable for the majority of actors in the real estate industry, a situation that may improve as industry expertise grows.

## 6.5 Building information systems with specific scope

An increasing number of BISs are now integrated with life cycle information management. This section analyzes a range of these systems, including real estate management tools (section 6.5.1) and more task-specific tools (section 6.5.2). Although their original functionality limits their suitability as comprehensive LC-BISs, their significance for actors of the real estate industry makes it essential to explore how they can complement traditional building-related information management.

## 6.5.1 Real estate management systems

### 6.5.1.1 Facility management systems

Facility management takes in an important role in building-related information management, since it is closest to a specific building compared to other real estate management disciplines and thus responsible for a majority of data collection throughout the use stage. According to standardization, facility management systems are supposed to determine policies, goals, and processes so that they contribute to the facility management goals of an organization (DIN EN ISO 41001:2018-09, p. 11). This implicitly includes the management of relevant building-related information which reflects in the analysis of the literature regarding covered data categories.

Facility management systems have evolved under the influence of digitization and technological advancement, summarized under the methodology of Computer-Aided Facility Management (CAFM). According to the literature, CAFM is a reaction to the increased complexity of operations in facility management (May, 2018, p. 2). CAFM systems work as individual facility management solutions for organizations based on CAFM software, a data basis as well as organizational and technical resources (May, 2018, p. 7). Further developed CAFM systems combine these functional units with virtual building models in integrated information systems (Opić et al., 2018, p. 46). There is also evidence about the interpretation of CAFM as a "digital building book" which should combine all tools that are relevant for facility management (VDI-MT 3810 Part 1:2023-03, p. 47).

While CAFM is a concept already existing for several decades, Talamo and Bonanomi (2015) follow a thorough approach how facility management can be supported by modern information systems. With an emphasis on building stocks from an organizations' standpoint, they propose a job-sharing approach between three main instruments with complementary functions:

- Real estate inventory: The purpose of the inventory is to collect all the relevant data necessary for facility management. Talamo and Bonanomi (2015, p. 32) describe the inventory as an "continuous process of retrieval, selection, validation, acquisition and updating of information". It is characterized by the progression, dynamism, and specificity of data collection as well as the appropriate level of detail and multiplicity of sources (Talamo & Bonanomi, 2015, pp. 32–33).
- Building registry: Talamo and Bonanomi (2015, p. 46) interpret a building registry as a knowledge base and information platform that stores the data collected in the inventory process. From a technical standpoint, a suitable database type needs to implement the building registry while facility managers should consider data quality requirements (Talamo & Bonanomi, 2015, pp. 46–48).
- Information system: Within this context, an information system is considered as a multifunctional instrument that supports actors in decision-making and operations simultaneously (Talamo & Bonanomi, 2015, p. 108). It is supposed to manage information gathered in the inventory and stored in the building registry and, above that, enable various processes of data retrieval, editing, and analytics (Talamo & Bonanomi, 2015, p. 109).

The described approach is a good example for advancing the functionality of facility management systems. However, it is niche topic, which did not find wider application in theory or practice.

Based on the findings from the literature review and the insights from expert interviews, benefits and limitations for facility management systems functioning as LC-BIS could be determined (Table 6.9).

Table 6.9: Benefits and limitations of facility management system, especially CAFM systems, for use as life cycle building information systems

| Benefits | Limitations |
|---|---|
| CAFM as an established concept in the real estate industry | CAFM already exists for several decades and is not perceived as an innovative approach |
| Substantial data need in facility management covers a large amount of life cycle building data | CAFM mostly concentrates on operational tasks during the use stage |
| Facility management is a discipline close to the building | Rather user-oriented and task-oriented compared to explicit building focus |
| Integration with virtual building models more and more common | Not designed to meet the needs of smaller companies and private building owners |
| | Often actor-specific solutions, not designed for data sharing across multiple actors |
| | Full potentials of CAFM systems are seldomly employed |

While facility management systems might not be suited to function as LC-BISs in their current form, they might be a very important information source when setting up LC-BISs.

#### 6.5.1.2 Portfolio and asset management systems

A fairly underrepresented group of tools in the academic literature concerns portfolio and asset management systems. This has multiple potential reasons:

- The relevance of support by information systems in portfolio management only grew in recent years along with growing building stocks of real estate and housing companies and the growing complexity of portfolio management
- Portfolio management is treated very differently from actor to actor in the real estate industry. While some companies run a dedicated portfolio management department, others still rely on “gut feelings” and prior knowledge. Changes can be observed with increasing professionalism in the industry. According to Rock and Seilheimer (2024, p. 195), large asset companies primarily develop customized ecosystems to support asset management and integrate it with other building-related task areas.
- There is a variety of job titles for portfolio managers. At the same time, many roles can be responsible for portfolio management tasks including investment, asset, risk, facility, or sustainability managers for example.
- Academics might not see reason to do research on portfolio management systems, since there is no need for substantial innovation.

Expert interviews revealed, however, that decisions in portfolio management are becoming increasingly complex due to more volatile markets, new requirements, e.g. by sustainability objectives, or new legal requirements. All these factors stress the need for decision support in portfolio management tasks, including portfolio analysis and risk management.

Portfolio management relies on a substantial amount of building-related data that must be collected on the building level. Insights from practitioners show that portfolio management software eventually stores the respective data in dedicated databases/storages or makes use of data from ERP systems (section 6.5.1.3), for example. However, a common problem is that these solutions are seldomly used longer than a couple of years. At the same time, they often do not meet the requirements on the functionality of users. These are just examples for barriers that prevent this type of tools to function as LC-BISs (Table 6.10).

Table 6.10: Benefits and limitations of portfolio management systems for use as life cycle building information systems

| Benefits | Limitations |
|---|---|
| Potential storage of a substantial amount of building-related data | Emphasize on portfolio level and not on single building level |
| Usually some kind of data quality standard implemented to ensure data for different buildings can be compared and aggregated | No standard regarding functionality and data content often leading to data interoperability issues |
| Oriented on practical needs of building owners | Usually focus on use stage only |
| | Only suited for a limited amount of building owners |
| | Not designed to share data |

More recent developments in the real estate industry show, according to expert insights, that portfolio management is not only assisted by dedicated portfolio management systems, but increasingly through digital twin solutions, especially in connection with sustainability assessments.

#### 6.5.1.3 Enterprise resource planning systems

Enterprise Resource Planning (ERP) systems are widely used in the real estate industry to manage organizational processes, focusing primarily on commercial operations such as finance, procurement, and resource planning. These systems are characterized by their structured data models, which support robust organization and traceability, and their ability to integrate data across multiple departments, enabling cross-functional insights. However, their historical emphasis on commercial processes often leaves them less suited for managing building-specific and life cycle-oriented data. Customization options exist but are often complex, time-intensive, and costly.

Expert interviews revealed that recent industry developments aim to address these limitations through the emergence of technical ERP systems. These systems are designed to complement traditional commercial ERP systems by incorporating building-related data and focusing on operational aspects such as facility and building management, maintenance, and sustainability reporting. This evolution highlights the growing recognition of building-related data as a critical resource, particularly in light of increasing demands for sustainability assessments and regulatory compliance. Despite these advancements, ERP systems show limited similarities with LC-BISs (Table 6.11).

Table 6.11: Benefits and limitations of ERP systems for use as life cycle building information systems

| Benefits | Limitations |
|---|---|
| Structured data models, supporting robust data organization and traceability | Historically focused on commercial processes, often neglecting building-specific needs |
| Integration across multiple departments, enabling cross-functional insights | Limited support for building life cycle stages beyond the use stage |
| Emerging technical ERP systems with focus on operational and sustainability data | Not designed for non-professional building owners and stakeholders |
| Cloud-based and modular architectures for scalability | Lack of interoperability with other building systems and data standards |
| | Customization is complex, time-intensive, and expensive |
| | Not designed for data sharing with external actors |

Building on the discussion of ERP systems, it is worth noting the growing potential of standard business software as an alternative or complement to traditional ERP solutions. Modern standard business software increasingly operates on cloud-based infrastructures, offering robust capabilities for document management, including metadata management, and providing seamless options for data sharing between different actors. These solutions benefit from being widely accessible, highly scalable, and often easier to implement than fully customized systems. However, their lack of customization options can be a significant drawback, particularly when dealing with highly specific building-related data requirements or workflows. Additionally, such software often struggles with treating granular data at the level of individual buildings or assets, which can limit its applicability for detailed lifecycle-oriented tasks. While these tools may not meet all the requirements of a LC-BIS, their flexibility and collaborative features make them an increasingly relevant component of modern building information management strategies.

### 6.5.2 Task-specific tools

#### 6.5.2.1 Building automation and management systems

Building automation and management systems (BAMSs) have already been introduced in the context of original data collection of dynamic data through sensor technology (section 4.1.3). Based on the many possibilities to collect real-time data via sensors in a building today, BAMSs need to handle large amounts of data. As indicated by industry experts, the sensors and devices integrated into BAMSs can vary significantly in their level of “smartness”, ranging from basic units that only collect measurement data, to more advanced components capable of local data processing, and up to devices that enable remote control and real-time interaction. Communication between devices needs to be coordinated through appropriate interoperable formats.

If used correctly, BAMSs can make significant contributions to a more efficient operation of building services. Among other things, BAMSs can help to improve energy efficiency, optimize water consumption, enhance safety and occupant comfort, reduce maintenance costs, and extend the service life of building components and services. For this, BAMSs rely on methods and technologies for big data analytics on the basis of AI and ML algorithms (Himeur et al., 2023, pp. 4932–4933).

However, the use of BAMSs can be challenging and not suited for all types of buildings and building owners. The literature identified current challenges in managing the data quality of raw data, using data for benchmarking, ensuring data security and privacy, and solving interoperability and scalability issues (Himeur et al., 2023, pp. 4987–4993). BAMSs tend to move closer to the functionality of a LC-BIS by incorporating new data sources and technologies. This stresses the importance of building-related information management. Regarding their relevance in the context of LC-BISs, several benefits and limitations could be identified, considering insights from expert interviews and knowledge (Table 6.12).

Table 6.12: Benefits and limitations of BAMSs for use as life cycle building information systems

| Benefits | Limitations |
|---|---|
| Collection, processing, storage, and analysis of large amounts of dynamic data | Integration of different kinds of static building-related data from all life cycle stages |
| Comes with potent ICT solutions | Usually high upfront costs for ICT infrastructure |
| In practice modular solutions available to cover different building management tasks and integration of different actors | Available solutions often designed for larger non-residential buildings only |
| Integration with virtual building models possible | Systems partly require expert skills and knowledge |

Despite their limitations, BAMSs and the digital collection and processing of data in general, might take in an important role in a modular approach on life cycle information management.

#### 6.5.2.2 Property registration and cadaster systems

Information systems for property registration and cadasters are becoming increasingly relevant for storing and maintaining building-related data. These systems play a significant role in supporting economic and social well-being (Adlington et al., 2021, p. 5). Two main functions underline their use cases: governments rely on them for land management tasks such as taxation, service provision, and infrastructure planning, while businesses and individuals use them for property transactions, mortgaging, and secure property management (Adlington et al., 2021, p. 6).

Recent trends highlight the evolution of property registration and cadaster systems. Traditional cadastral data are increasingly enhanced to include more detailed information. For example, in Germany, the Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany (2023) maintains 3D building models at BIM LoD 100 and 200, enabling applications such as energy demand estimations, solar cadasters, and emergency management. Private initiatives, such as those from Geomer (2025) provide structured datasets on building stock and characteristics based on geospatial analysis. Simultaneously, building registers are emerging that focus on the building stock rather than solely spatial aspects. Germany is considering the introduction of a national register for buildings and dwellings. According to Krause et al. (2022, pp. 27–28), such a register could:

- Enable consistent and less resource-intensive statistical surveys of the building stock,
- Provide building-related data for real estate and academic research,
- Support a more efficient and digital building permit process,
- Facilitate monitoring of energy efficiency and greenhouse gas emissions,
- Aid in housing needs assessments and funding allocation.

Other countries such as Denmark (Christensen, 2011, p. 106), Estonia (Estonian Centre of Registers and Information Systems, 2021), Iceland (HMS, 2023), or Switzerland (Federal Statistical Office, 2023) have introduced building registers that extend beyond traditional cadastral systems in data scope and functionality (section 3.3.5).

The suitability of these systems as LC-BIS depends on their focus and functionality. Traditional cadasters and land registers are less appropriate, whereas modern building registers are evolving toward a more comprehensive management of building-related information. Promising examples, as from Denmark, indicate that these systems can offer a robust foundation for accessing key master, inventory, and legal data. Limitations to their function as LC-BIS relate to the management of dynamic data and, most notably, to issues of data ownership and control. Compared to building owners and real estate management professionals, the public sector typically lacks the capacity to effectively administer data collection, storage, sharing, and quality management, which are essential for numerous lifecycle tasks. Moreover, in countries such as Germany, where no building register currently exists, the time and cost associated with its development would be considerable.

#### 6.5.2.3 Tools for sustainability assessment and management

The increasing demand for sustainable practices in the real estate industry has led to the proliferation of tools and systems designed to assist in sustainability management. These systems aim to support building owners and other actors by offering knowledge about assessment methods, automating evaluations, assisting with data collection and management, visualizing results, and generating automated reports for internal and external stakeholders. Their functions are closely tied to consulting services within the real estate industry, making them an integral part of sustainability-oriented decision-making. Although the academic literature provides little to no evidence on this group of tools, expert interviews indicate that they are a highly relevant and current topic for practitioners.

Many of these initiatives are spearheaded by proptech companies and new players in the field, reflecting the dynamic and innovative nature of this domain. These solutions are predominantly business-to-business (B2B) and tailored for housing companies, real estate funds, project developers, financiers, and other professional entities (C. Schäfer, 2024, p. 13). The focus spans diverse sustainability topics, including fostering ESG principles. Key areas of application include calculating GHG emissions, developing decarbonization strategies, exploring climate adaptation possibilities, and formulating asset and portfolio strategies. Increasingly, these systems also assess the financial implications of sustainability measures at both the building and corporate levels, and some offer solutions for evaluating circularity potential (C. Schäfer, 2024, pp. 8–9).

The most sophisticated systems in this domain leverage standardized methodologies, such as LCAs, to ensure reliable and actionable insights. These systems are often implemented as cloud-based platforms that require substantial building-related data. To address this need, service providers frequently assist building owners in data collection processes, such as through building surveys or due diligence services. The collected data are stored in databases, in some cases with interfaces to ERP systems or other corporate information systems.

Sustainability management imposes significant requirements for systematic building-related data management, making it a strong driver for the development of LC-BISs. Current service providers demonstrate effective examples of how modern ICT infrastructures can be utilized to create practical BIS solutions tailored for sustainability use cases. Some solutions already integrate advanced technologies, such as digital twins, offering decision support not only for sustainability management but also for portfolio management, facility management, financial planning, marketing, and risk management.

However, the current landscape also presents notable limitations. Most solutions are tailored to specific groups of actors, primarily large real estate companies, often excluding smaller enterprises and private building owners. The scope of data in these systems is typically restricted to serve immediate use cases, which risks creating new silos of information. Furthermore, many systems exhibit poor interoperability with other data formats and information systems, compounded by the risk of vendor lock-in effects. Another critical shortcoming is the lack of focus on how collected data should be maintained and updated over the long term, raising questions about the sustainability of the data management practices themselves.

## 6.6 Discussion of findings

This section synthesizes the findings from the analysis of existing BISs. It first provides general observations to contextualize these findings within current developments and trends (section 6.6.1). Next, it compares selected BISs, assessing the extent to which they meet the requirements of a LC-BIS (section 6.6.2). This is followed by an exploration of potential synergy effects between their functionalities (section 6.6.3). Finally, methodological limitations are briefly addressed (section 6.6.4), and a concluding reflection prepares the groundwork for the results section of this thesis (section 6.6.5).

### 6.6.1 General observations

BISs have historically evolved in response to the complexity of information management across the building life cycle. This analysis does not question the general functionality of these systems but rather evaluates their applicability as LC-BISs aimed at overcoming typical challenges in the industry.

A notable trend across all BISs is their evolution toward more data-centric approaches, driven by technological advancements and digitization. This shift underscores the growing importance of interoperability between data formats and systems. In addition, the overlay of different trends across the real estate industry, mainly driven by sustainability reasons, which increases the need for building-related data can be observed within the landscape of BISs. This complicates it further to distinguish between different systems and their functionality, while it is already difficult to receive a bigger picture of relevant BISs that are relevant to the real estate industry now and in the future.

Another aspect addresses the diverse set of terms, contributing to misconceptions and uncertainty, especially among practitioners. For instance, building passports though rooted in longstanding concepts and first implementations, now gain prominence more recently under the term “digital building logbook”. At the same time, the concept of "passportization" has introduced further ambiguities, with terms like material passports and renovation passports often conflated with building passports. This leads to a lack of reliability in practice, where the term may, in the worst case, suggest a fundamentally different system due to a conceptual misunderstanding. In addition, other BISs which were originally applied for more specific tasks now move to the functionality of LC-BISs.

### 6.6.2 Fulfillment of requirements and implications

Table 6.13 presents a heat map indicating the extent to which various BISs meet the requirements of a LC-BIS. The findings are based on the literature review, while the comparison categories are drawn from the requirement profile in chapter 5. For simplicity and better clarity, not all identified BIS types are listed. Instead, the selection includes relevant passport concepts (DBPs/DBLs, material passports, and renovation passports) and virtual building model applications. Additionally, real estate management systems and building registers are considered as grouped categories.

Regarding the main functions, it can be observed that all systems have the potential to cover a substantial amount. Especially passport concepts are designed to function as data repositories, highlighting their respective relevance. Virtual building model applications show their main strength in visualization, which is inherent to their character as a digital copy. Most systems have the capability to assist data collection, facilitate data sharing, and data quality management, while also active decision support plays a role, especially through action plans, such as in renovation roadmaps. Naturally, the extent to which these functions are covered in practice depends on the individual tool applied.

Slight differences can be seen in life cycle coverage. While DBPs/DBLs are intended to cover the use stage through to the end-of-life of a building, virtual building models, despite advancements towards life cycle management (section 6.4.1), are still largely focused on the construction stage. This is due to their strong emphasis on geometric data and their still-limited adoption in practice, as indicated by expert interviews. Material passports show the highest relevance in (de-)construction stages, whereas renovation passports are specifically designed for existing buildings. In general, DBPs/DBLs, virtual building models, and material passports contribute to a better transfer of data from early life cycle stages to the use stage.

Differences become apparent when looking at data coverage. DBPs/DBLs are designed to include all essential data categories, whereas other BISs tend to focus on more specific domains. Virtual building models, due to their focus on geometric data, effectively cover inventory data and can also include performance data, particularly when realized as semantically rich digital twins. Real estate management systems, such as facility management or ERP systems, have strong capabilities in managing master data as well as economic and legal data. However, they often lack clearly defined system boundaries at the individual building level, which limits their ability to comprehensively cover inventory and performance data.

Substantial differences also exist regarding costs. While DBPs/DBLs aim to provide low entry barriers for all types of actors throughout the building life cycle, virtual building models are regarded as expert tools among industry practitioners. This is considered one of their major downsides, as it limits accessibility for a broader range of actors.

The potential to meet data quality requirements is closely tied to the level of data structuring within a BIS. Virtual building models, when applied with structured data formats such as IFC, show strong capabilities in meeting accuracy, consistency, and interoperability requirements. On the other hand, DBPs/DBLs, due to their broader range of addressed actors and data categories, have a higher potential to provide data that is complete and comprehensible for users. Other systems do not exhibit particular strengths in this regard.

Regarding system-related requirements, DBPs/DBLs are designed to be easy to use and scalable. While virtual building models are also scalable, they lack ease of use for most actors.

Table 6.13: Comparison life cycle building information system requirement compliance across different systems

| | | DBPs/DBLs | Virtual building model applications | Material passports | Renovation passports | Real estate management systems | Building registers |
|---|---|---|---|---|---|---|---|
| Potential to support main functions | Data storage | | | | | | |
| | Data collection | | | | | | |
| | Data sharing | | | | | | |
| | Quality management | | | | | | |
| | Visualization | | | | | | |
| | Assessment | | | | | | |
| | Active decision support | | | | | | |
| Life cycle coverage | Development | | | | | | |
| | Construction | | | | | | |
| | Use | | | | | | |
| | End-of-life | | | | | | |
| Data coverage | Master data | | | | | | |
| | Inventory data | | | | | | |
| | Legal and economic data | | | | | | |
| | Performance data | | | | | | |
| Costs | Level of expertise required | | | | | | |
| | Initial setup costs | | | | | | |
| | Administration effort | | | | | | |
| Potential to meet data qualities | Accuracy | | | | | | |
| | Availability* | | | | | | |
| | Consistency | | | | | | |
| | Interoperability | | | | | | |
| | Security | | | | | | |
| | Completeness | | | | | | |
| | Non-Redundancy | | | | | | |
| | Comprehensiblity | | | | | | |
| | Usefulness* | | | | | | |
| Potential to meet system requirements | Interoperability | | | | | | |
| | Modularity, granularity | | | | | | |
| | Operability, Ease of use | | | | | | |
| | Scalability, expandability | | | | | | |

*Depends on external factors, no clear assumption possible

### 6.6.3 Synergies

BISs are not inherently exclusive: synergy effects become apparent when they are deployed in a modular, job-sharing framework that aligns under a unified framework. While DBPs/DBLs show their suitability as LC-BISs, other BISs can make substantial contributions, including material passports for material-related information, renovation roadmaps for decision support in renovations, as well as virtual building models for visualization, modeling, and simulations. Likewise, interfaces with real estate management systems and other task-specific tools must be determined. The modular implementation of BISs will therefore be considered in the results section of this thesis (section 7.6.3). A rough classification on the data scope of relevant systems has already been made in an earlier paper by the author (Buchholz & Lützkendorf, 2022a). While this classification only shows a selection of potential data categories and does not consider all the capabilities, it illustrates the respective focal points (Figure 6.8).

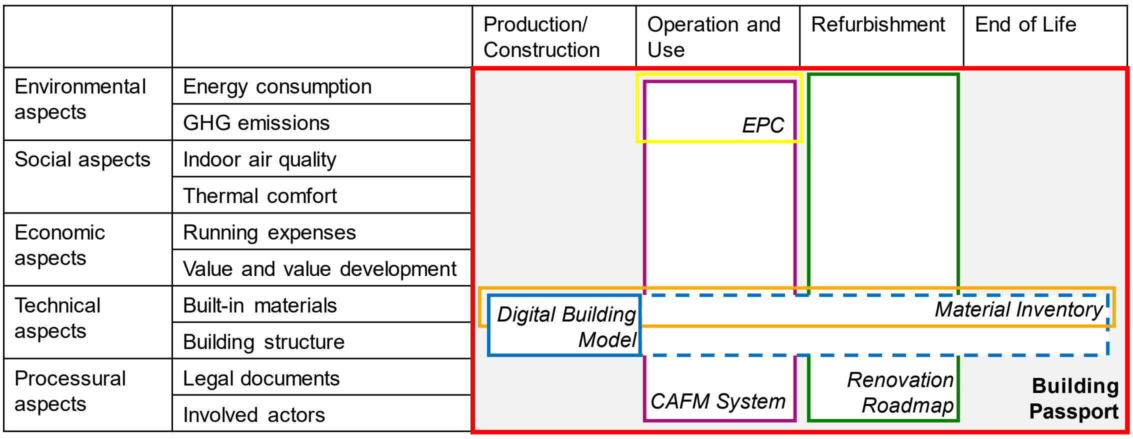



Figure 6.8: Data related focal points of selective building information systems throughout the life cycle (Buchholz & Lützkendorf, 2022a, p. 6, 2023, p. 914)

### 6.6.4 Methodological limitations

This review captures only a snapshot of a rapidly evolving field. The analysis primarily reflects academic perspectives, which may not fully align with industry realities. While expert insights were incorporated, the scope of empirical studies remains limited, particularly regarding diverse actor perspectives and regional differences beyond Europe and Germany. As a result, the global applicability of the findings remains partially unexplored.

The evaluation and discussion of BIS capabilities present an aggregated and abstract view of these systems, which may not fully align with specific industry applications that are often more heterogeneous in functionality. The aim was to provide a structured overview and comparison by logically grouping BISs based on the current state of knowledge. Given the dynamic nature of this field, the classification and findings should be understood as reflective of the current landscape rather than a definitive assessment.

A systematic literature review inherently focuses on published studies, which do not always capture practical applications. Expanding future research through additional empirical approaches, such as case studies or broader industry engagement, could provide deeper insights into the real-world implications of BISs across different contexts.

### 6.6.5 Conclusion

The overall findings of the analysis in this chapter indicate that:

- The concept of a LC-BIS is not completely new to the real estate industry and that more and more BISs move towards this idea. This means that the development of a LC-BIS can fundamentally build on existing approaches.
- DBPs/DBLs exhibit the highest potential to function as LC-BISs for the majority of actors. These systems align closely with the requirements outlined for LC-BISs, particularly in terms of their capacity to support data-centric, modular, and low entry approaches. While virtual building models might also take in an increasing role for specific actors in life cycle information management, other tools rather function in a complementary way.
- Significant gaps remain in understanding how these systems can fully meet the requirements on a LC-BIS. Specifically, further clarification is needed on their functionality, the processes by which they can address life cycle-specific information management challenges, and the pathways for successful implementation within the industry.

Based on this conclusion, the functionality of LC-BISs will be specified for DBPs/DBLs in the results section (chapters 7 and 8). For this, unresolved aspects including the technical mechanisms by which DBPs/DBLs can fulfill life cycle coverage, the seamless information transfer across life cycle stages, and the accessibility for diverse actors will be addressed. Additionally, practical strategies for integrating DBPs/DBLs into existing workflows, addressing economic viability, and overcoming barriers to adoption in the industry are essential to realize their potential. For simplicity and based on the longer history among practitioners within the industry, the term ‘building passport’ will be used as a basis, while ‘digital’ clearly indicates that the tool is no longer a simple hardcopy document collection, but a digital tool.

# III Results and proposals

# 7 Proposal of digital building passports as life cycle building information systems

*Building on the analysis in Part B, this chapter presents the primary proposal of this thesis. It develops a conceptual framework in the form of an information systema architecture (ISA) for DBPs, identified as the most suitable tool to serve as a LC-BIS. The chapter draws on foundational concepts from chapter 2, including the interpretation of an ISA and various information modeling approaches.*

*A condensed version of this framework was previously presented by the author in an earlier publication (Buchholz & Lützkendorf, 2024). In this chapter, the framework is refined and expanded with greater detail. The process begins with an explanation of how the ISA is derived, outlining the assumptions and providing an overview (section 7.1). Each view of the system is then addressed, explaining how its respective sub-elements are derived (sections 7.2 to 7.6). The chapter predominantly applies a conceptual and semantic perspective, while also offering more specific explanations of technical implementations where necessary. The systematic derivation of the ISA elements inherently incorporates a verification process.*

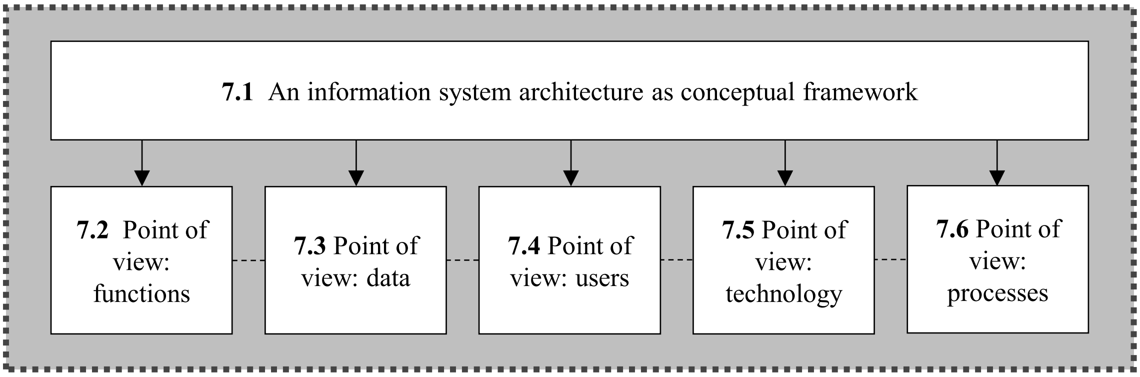



Figure 7.1: Structure of chapter 7

## 7.1 An information system architecture as conceptual framework

In this section, the conceptual framework is derived for DBPs in their role as LC-BIS. It comes in the form of an ISA, which is a suitable instrument to define the most important elements of an information system. After deriving the structure of the ISA (section 7.1.1) and providing a visual overview (section 7.1.2), the approach is compared to existing reference architectures (section 7.1.3). In addition, the relevance of system boundaries is explained (section 7.1.4).

### 7.1.1 Derivation and assumptions

An ISA enables a structured view of an information system including a descriptive representation of all constitutional elements so that it can be developed, used, and maintained according to requirements (section 0). Several reasons speak in favor of adapting the architecture concept for DBPs too:

- Conceptual view: An ISA is easy to understand also for non-experts since it does not rely on formalization mechanisms. In addition, it provides a semantic view on an information system.
- Abstraction, modularity: An ISA can be represented by conceptual models on different levels of detail. A modular approach supports the abstraction for different elements.
- Completeness: An ISA covers all relevant aspects of an information system. It follows a life cycle approach so that it can be used during design, creation, and use of the system.
- Perspective: An ISA enables to take in the different views of the single elements on the complete information system. These views can also be interpreted as dimensions and constitute the elements of the system.
- Scalability, expandability: An ISA can be enhanced based on the modular approach.
- Adaptability, flexibility: An ISA can be used and adapted for various use cases based on its characteristics of completeness, abstraction, and perspective.
- Clear system boundaries: An ISA defines system boundaries implicitly by defining the elements of the system and explicitly by defining interfaces with the system environment.
- Reference: An ISA is an appropriate concept for the real estate industry, since the actors can relate to the term ‘architecture’ and to its meaning quite well.

Thus, a suitable ISA for DBPs needs to be derived that meets the requirements on a LC-BIS as defined in chapter 5. The goal is to determine necessary elements, also called building blocks or modules, and to explain how these elements are interrelated. The single elements enable different views on the system and can be organized in subarchitectures. This emphasizes the abstract and modular view on an ISA.

An ISA for DBPs must first and foremost incorporate the relevant *functions*. Functions define the tasks performed by the system or in interaction with it. By establishing a dedicated element for functions within the ISA, these tasks can be analyzed and explained independently. At the same time, functions must be interconnected with other key elements of the system, such as relevant data, users, and technological resources. Only through these interconnections can functions become meaningful and meet user requirements. The functions of a DBP are shaped by its role as a data repository and by the information management processes that support this role.

The second essential aspect is the data included in the ISA. To develop a robust *data architecture*, the ISA must enable an independent conceptual perspective on data. The data element should specify how data are structured at the semantic, logical, and physical levels. A well-defined data architecture ensures that data are created, collected, processed, stored, retrieved, shared, analyzed, and updated in accordance with system requirements. Data also play a central role in system interactions, serving as both inputs and outputs for various functions.

A third fundamental element of the ISA is the *system users* and their characteristics. Since information systems are socio-technical systems, comprising both human and machine elements, users must be explicitly considered. Within the ISA, users are characterized by their interactions with other system elements at different points in time. Additionally, they vary in terms of personal and organizational factors, including their knowledge of system functions, specific requirements, professional context, preferences, and challenges. An ISA must accommodate these differences by implementing a structured approach to managing user interactions. This requires a framework that is both stable and adaptable, ensuring that the system can respond to evolving user needs while maintaining necessary information flows.

Another crucial element of the ISA is the technological infrastructure, specifically *information and communication technology* (ICT). Digitization and automation are essential for meeting data quality and system-related requirements in a LC-BIS, particularly when multiple quality attributes must be achieved simultaneously. Therefore, ICT should be explicitly integrated as a separate element within the ISA. While ICT is relevant to all system elements, treating it as an independent component offers distinct advantages. First, digital DBPs are still emerging, meaning that potential users require transparency regarding the implemented technologies and their benefits. Second, the rapid evolution of ICT necessitates a flexible approach that allows new technologies to be assessed and integrated at the system level, rather than requiring modifications to individual elements. Additionally, maintaining ICT as a distinct element facilitates an independent and focused evaluation of technological performance.

While these four elements, functions, data, users, and ICT, form the core of the ISA, they must be interconnected and aligned with external entities beyond system boundaries. To manage these interactions, an additional element is required: the *process element*. This component governs the execution of system functions and facilitates interactions between the internal elements as well as between the system and its external environment. It acts as a control unit, defining rules and mechanisms to respond to both internal and external triggers that necessitate action. This includes coordinating the execution of functions while integrating human, technical, and data-related resources.

### 7.1.2 Architecture model

The ISA for DBPs, comprising the five identified elements, can be illustrated through an architecture model. At this level of abstraction, the model does not adhere to any specific modeling language or formalization mechanism. Instead, it focuses on representing the elements and their relationships. The arrangement of the elements is guided by straightforward considerations: the user viewpoint is positioned at the top, emphasizing the overarching requirement for the system to be useful to its intended users. Data and functions, which are interdependent system elements, are placed horizontally at the center. Neither can fulfill its purpose without the other. The ICT implementation is situated at the bottom, reflecting its supporting role. The entire architecture is unified through the process perspective, a central control element, which connects and integrates all components within the ISA (Figure 7.2).

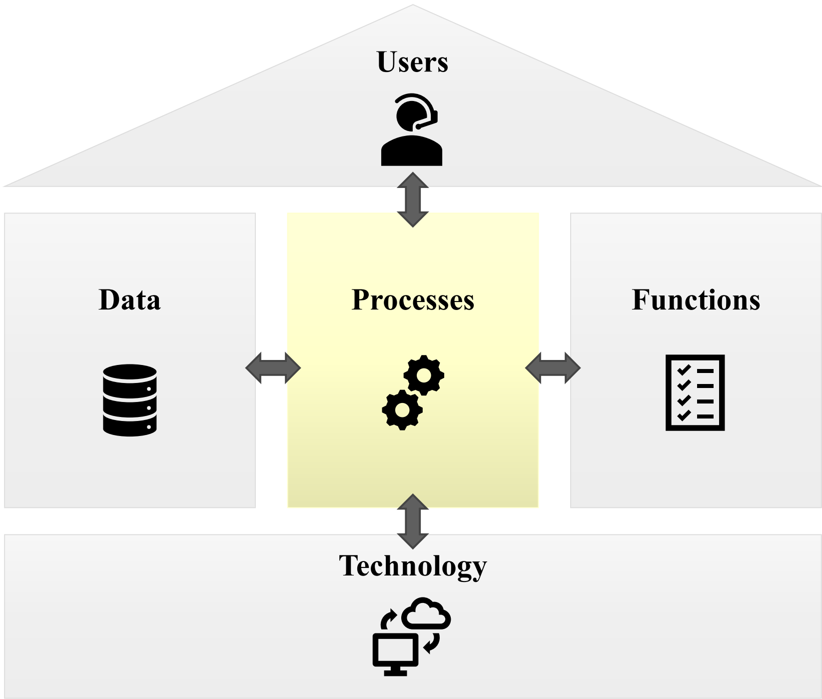



Figure 7.2: Information system architecture model for digital building passports based on Buchholz and Lützkendorf (2024, p. 6)Each element of the system will be specified individually in the following sections of this chapter. This approach ensures a clear and detailed understanding of each component, its role within the architecture, and its interactions with other elements.

## 7.1.3 Link to existing reference architectures

There are ISAs that act as overarching frameworks providing guidance for specific architectures (section 0). These frameworks, which are called reference architectures, were analyzed to identify similarities to the ISA for DBPs. A severe similarity could be identified with the architecture of integrated information systems (ARIS) by Scheer (1998, p. 18).

Three elements of the ISA for DBPs, function, data, and the control/process view, align with those in the ARIS framework (Table 7.1). This raises questions about the distinctions between the remaining elements, their origins, and the potential implications these differences hold for the ISA for DBPs. Exploring these aspects will provide insight into how the ISA for DBPs diverges from the ARIS framework and what this means for its design and application.

Table 7.1: Comparison of the proposed information system architecture for digital building passports with ARIS

| ISA DBPs | | ARIS framework |
|---|---|---|
| Users | vs | Organization |
| Functions | vs | Functions |
| Data | vs | Data |
| ICT | vs | - |
| Processes | vs | Processes |
| - | vs | Performance |

For DBPs, the human element is explicitly represented through the perspective of users, whereas the ARIS framework addresses this aspect implicitly via the organizational view. This distinction can be attributed to the differing contexts of the ISAs. As common for foundational concepts in business informatics, Scheer (1991) developed the ARIS framework within the context of intraorganizational information systems. Historically, a primary focus of information systems research was on the development, management, and optimization of ICTs for business organizations. The term “integrated” within ARIS underscores this focus, emphasizing its design for implementation within such systems. However, the demand for interorganizational information systems has grown significantly since the time ARIS was introduced. This shift is also relevant for DBPs, which are envisioned as tools serving a diverse range of actors. Consequently, the user element in the ISA for DBPs explicitly incorporates the users’ perspective, independent of their specific organizational context, which lies outside the scope of the ISA.

In his early work, Scheer (1991) proposed a separate integration of technological aspects within the ISA framework. However, he later abandoned this approach, emphasizing that ICT is inherently embedded in all elements of an ISA through their technical implementation. This perspective is rooted in the scheme of descriptive views, which range from the conceptual business view to the physical technical view, and are intrinsic to all elements of the framework. The same logic applies to DBPs. Nonetheless, due to factors discussed earlier, such as the novelty of DBPs and the rapid pace of technological advancements, ICT is treated as a standalone element within the ISA for DBPs. Differences between conceptual and technical views will be addressed in the following sections for specific elements.

In more recent versions of ARIS, another view was added focusing on performance aspects (Scheer, 2001, p. 93). This includes the outcome of production and service processes of a company, for which the ARIS framework is applied. Since the ISA for DBPs is explicitly designed to serve information management and not to model production and service processes, this view is not relevant for this context.

### 7.1.4 System boundaries

System boundaries define the separation between the system and its environment, playing a critical role in ensuring the system's functionality over its lifespan. For a DBP, establishing clear boundaries is essential to distinguish it from its surrounding environment. However, this task is inherently complex, as DBPs in their role as information systems are multi-dimensional constructs shaped by their socio-technical nature, integrating both technical components and human factors.

In theory, it is sufficient to clearly define all entities within a system in order to define its system boundaries. This is based on the assumption that all other entities are not part of the system. Still, this includes difficulties, since:

- DBPs are open information systems that interact with their environment frequently,
- DBPs are dynamic information systems which means that they change through time including their elements,
- DBPs are artificially separated from their environment, a crucial aspect as information systems increasingly operate in decentralized and virtual environments rather than being tied to specific physical locations.
- Numerous entities of the real world could potentially be an integral part of the system,
- DBPs can be extensive systems with a variety of data, functions, users, and technologies.

These features have several implications. For instance, specific entities do not need to be part of the system both conceptually and physically at the same time. Data can be semantically integrated using technologies like linked data, even when physically stored at a location different from where it is accessed. The dynamic nature of a DBP also allows entities to be included in the system temporarily. This is particularly evident in the case of users, who, as individuals in the real world, possess unique characteristics. When they interact with a DBP, they take on the role of users with distinct features, such as motives, requirements, knowledge, access rights, and previous actions, that collectively define their identity within the system.

In order to better define system boundaries for the single elements and decide whether an entity is part of the system or not, several criteria are applied for the definition of ISA elements. These can also be interpreted as minimum requirements (Table 7.2).

Table 7.2: Implications on system elements to define system boundaries

| System element | Possible criteria for system boundaries | Implications |
|---|---|---|
| Data | Building reference<br>Minimum data quality requirements | A data structure should be oriented on the main object of consideration, primarily a single building in various states of its life cycle. It should fulfill minimum requirements on data quality to meet the requirements of users. |
| Functions | Minimum user-specific requirements<br>Differentiation from other BISs | Functions should be oriented on the requirements of users. In combination with other system elements, a clear differentiation to other BISs must be possible. |
| Users | Minimum requirements on user attributes based on access policy | The system should only incorporate users with a reasonable purpose for access. Thus, suitable user attributes must be chosen to constitute user models and manage access. |

| | | |
|---|---|---|
| ICT | Necessity for functioning of other ISA elements<br>Added value through quality improvements (e.g. higher effectiveness, efficiency of processes) | Only those ICT resources should be incorporated that are substantial for the system to function properly or that provide specific added value. User requirements should be considered too. |

The system boundaries of a DBP are influenced by the boundaries of its object of consideration. As outlined in the requirement profile (section 5.2.1), the DBP focuses on individual buildings and their inherent characteristics. This reference point affects several elements of the system. In the case of buildings with multiple owners, for instance, both the data element (e.g., separation between shared and unit-specific data) and the user element (e.g., differentiation in data ownership and access rights) must be handled differently compared to buildings with a single owner.

The requirements on system boundaries, as laid out in Table 7.2, can be visualized by placing the internal elements of the information system at the center surrounded by external entities.

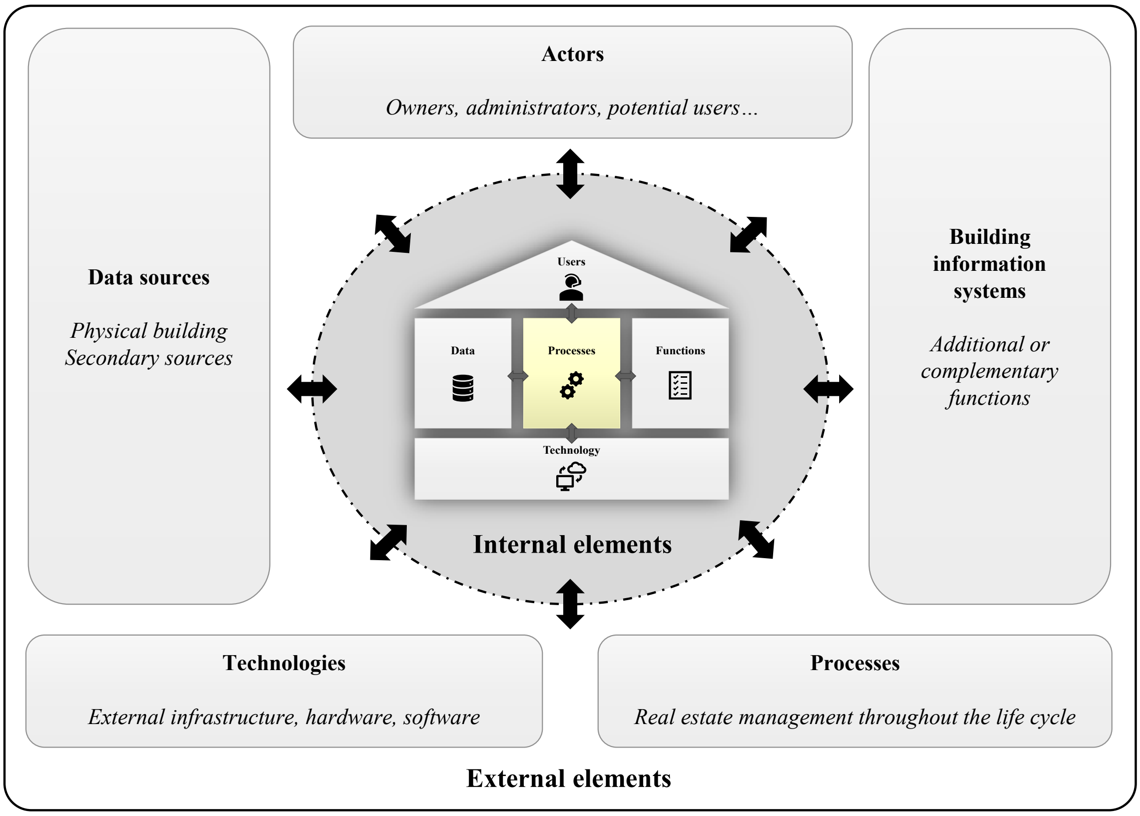



Figure 7.3: Overview on system boundaries for digital building passports

It becomes evident that all internal elements of the ISA have external counterparts. Clearly distinguishing between these perspectives, but also acknowledging the mutual information flows is key to specify the functionality of the system. System boundaries for single elements will be considered, where appropriate, in the following sections. Special emphasis will be laid on potential job-sharing possibilities between DBPs and other BISs as part of the process element (section 7.6).

## 7.2 Point of view: functions

### 7.2.1 Derivation and assumptions

In the literature on BISs, and specifically on DBPs, authors frequently attempt to define the functions that such systems should include (section 6.2.3.1). However, many of these proposals lack a methodological foundation and do not aim to provide a comprehensive overview. Often, they merely highlight a subset of potential functions without specifying them in detail. One significant reason for this lack of thorough explanation is the ambiguous use of the term “function”, which is variably interpreted as a goal, process, operation, task, requirement, and more. This inconsistency creates confusion among the addressed actors.

To establish a subarchitecture for DBP functions, a function is interpreted as a process comprising one or more tasks, serving one or more goals, and fulfilling the system's functional requirements. For instance, “data collection” can be considered a function that encompasses various processes, integrating human, data, functional, and technological perspectives. The goal of this function is to collect specific building-related data so they can be stored, shared, analyzed, or otherwise utilized in alignment with predefined requirements.

Within the ISA, functions are treated as static objects to enable their definition and modeling independent of other views. In contrast, processes, as defined in the process element, integrate all system elements to represent dynamic changes and interactions. This distinction ensures clarity between the static definition of a function and the dynamic representation of processes within the DBP.

To receive a better overview on the function element of the ISA, a model is proposed that uses a hierarchical structure. Thus, a function can be defined on several levels of details so that a number of subfunctions can be integrated. The chosen structure in combination with the interpretation of the term ‘function’ allows for a framework in DBP development and use with several characteristics:

- Adaptable and adaptive: The model can be customized for specific practical use case scenarios by adding, redefining, removing, or (de-)activating specific functions.
- Clear: A hierarchical structure ensures the clear allocation of functions to their overarching counterparts, preventing the conflation of simple functions with more complex ones.
- Flexible: The model enables several mechanisms to group functions. They can be grouped according to the similarity of the involved process, the object that is focused, or the similarity of the context in which functions work together.

- Compatible: The model serves as a solid foundation for assigning human, technical, data-related, and other resources to specific functions. It makes the question of who should perform each function and how it should be executed more concrete and actionable.
- Life cycle perspective: The proposed structure is versatile and can be applied across different life cycle stages of the information system. While the focus is on functions within the use stage, it can be seamlessly adapted to the design and development stage by maintaining the same objects of consideration and reframing the context to address ‘development’ instead of ‘management.’.

### 7.2.2 Function model

The hierarchical structure of functions can be visualized as a function tree composed of nodes and edges, where all functions can be traced back to a single root node (Figure 7.4). The first level of differentiation distinguishes between “inherent functions”, which are essential for the system's proper operation, and “built-up functions”, which build on this foundation to fulfill user requirements. Both inherent and built-up functions represent complex bundles, each comprising various subfunctions that collectively contribute to the system's overall functionality. In a specific application these subfunctions can be interpreted as modules.

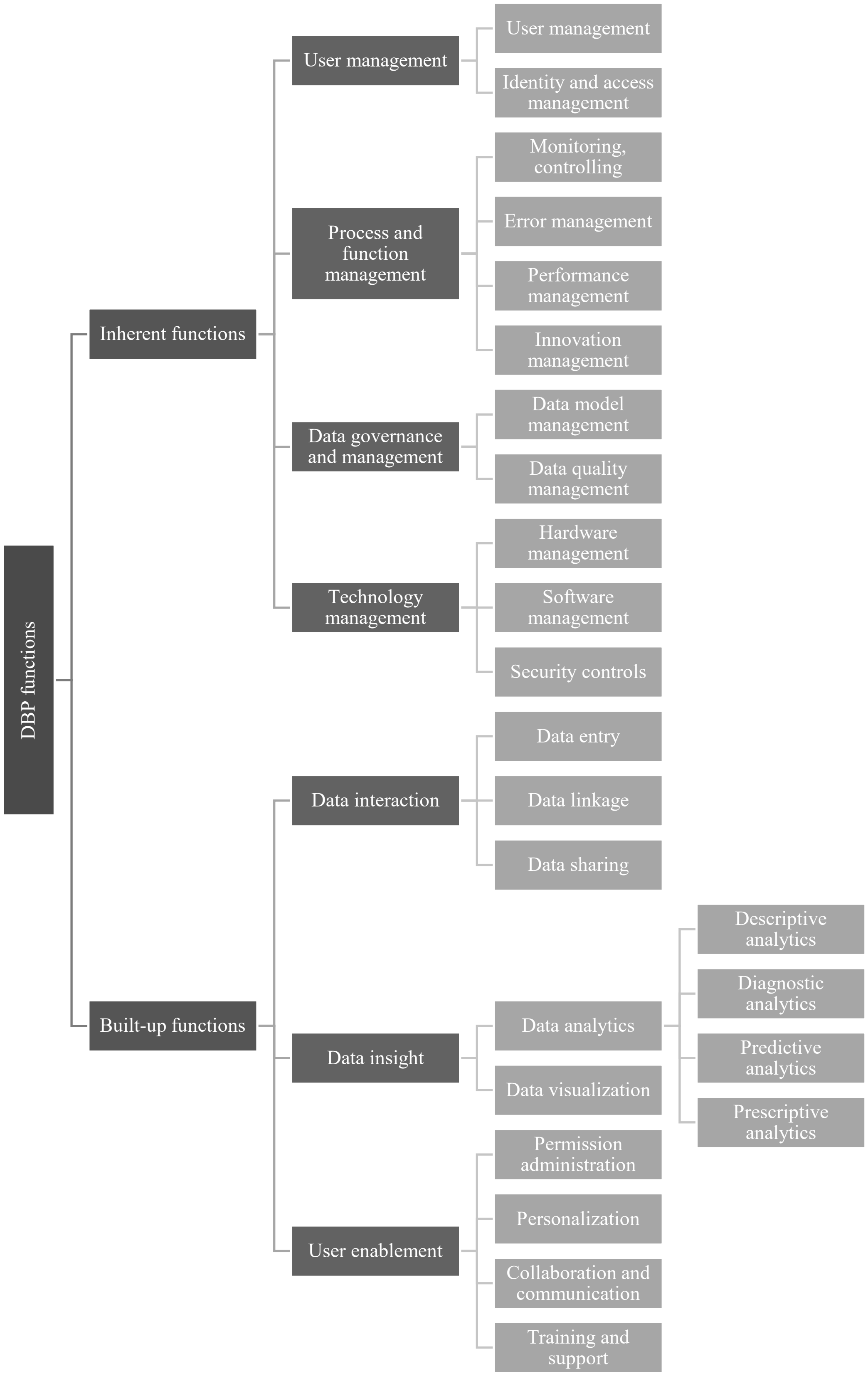



Figure 7.4: Function tree for digital building passports based on Buchholz and Lützkendorf (2024, p. 9)

*Inherent functions* are fundamental to the realization of DBPs as an information system and are critical for meeting system-related requirements, such as availability, controllability, maintainability, ease of use, and security (see section 5.6). These functions can be categorized according to the elements of the ISA, encompassing the management of the user, data, function, ICT, and process elements. Each of these categories consists of further specific function bundles, underscoring the complexity of representing the full spectrum of functions within a single framework. Based on their close correlation it was decided to integrate process and function management. At this stage, the function tree will not be further detailed, as relevant aspects of managing specific ISA elements are addressed in their respective sections.

The *built-up functions* of a DBP create value for its users by addressing their specific information management needs. These functions are derived from the requirements of actors in the real estate industry, as explored in Chapter 3 of this thesis, and reflect a systematic translation of those requirements, as discussed in sections 5.2 and 5.3. Built-up functions are classified based on their roles in interacting with building-related data and enabling users to derive insights or take action.

The *data interaction* functions focus on enabling users to insert, exchange, link, and share building-related data efficiently. Data entry includes processes for incorporating original data, such as measurements or manually inputted data, and integrating secondary data, such as data imported from external systems or linked from other sources. Data linking serves to associate and connect related datasets, improving the system's ability to provide a coherent view of building-related information. Data sharing empowers users to securely distribute data or grant access, supported by access control mechanisms that allow data owners to define and monitor permissions. These processes ensure that users maintain control over their data while facilitating collaboration and information exchange.

*Data insight* functions enhance the value of a DBP by enabling users to analyze and interpret building-related data. Advanced data analytics play a crucial role in transforming a DBP from a passive data repository into an active decision-support tool, leveraging digitization and automation. The role of ICT in this context is detailed in section 7.5.3.6. The potential of data analytics functions becomes particularly evident when examining use cases linked to specific data points, such as predictive maintenance or performance assessments (section 7.2.3). Additionally, data visualization enables users to interact with data through filtering, aggregation, and intuitive presentation, facilitating decision-making and improving comprehension.

The *user enablement* functions ensure that users can effectively utilize the DBP and maintain control over their data. Access control is central, allowing data owners to define and manage permissions, ensuring secure and transparent data usage. Personalization enables tailored workflows, notifications, and custom views that adapt to user needs. Collaboration tools support multi-actor interactions, offering shared workspaces and version tracking. Finally, guidance and support functions, such as tutorials and adaptive prompts, help users navigate the system and maximize its utility.

This classification reflects the interconnected nature of these functions, where data interaction serves as a foundation for data insight and user enablement. Together, they provide a comprehensive framework for addressing the diverse information management requirements of DBP users while ensuring usability, security, and value creation.

### 7.2.3 Specification of analytical functions for selected use cases

The built-up functions of a DBP are inherently versatile and reveal their full relevance only within specific use cases. Use cases emerge from processes within the system, whether triggered internally or externally, integrating various system elements. While use case specification technically belongs to the process element, it is included in this section to provide a logical context for functions.

Data analytics functions offer significant potential to enhance DBPs beyond earlier building passport developments. Since this potential remains largely untapped, Table X presents proposals for their application in selected use cases, with a focus on the use stage due to its critical role in real estate management.

The specified functions leverage various types of data analytics, with particular emphasis on:

- Diagnostic analytics, e.g., performance monitoring and anomaly detection
- Predictive analytics, e.g., service life estimations for building elements
- Prescriptive analytics, e.g., performance optimization proposals

In conjunction with user enablement functions, particularly personalization, actors can utilize data analytics based on their specific needs and preferences. The diversity of functions highlights the need for customization, as implementation often depends on situational goals, user requirements, and external framework conditions.

Table 7.3: Overview on data analytics functions proposed for digital building passports

| Use Case | Functions |
|---|---|
| Maintenance | Automated memory function for inspection and routine maintenance tasks |
| | Condition analysis of building elements with predictive estimation of remaining service life |
| Modernization / renovation | Automated identification of modernization options based on building data |
| | Generation of renovation roadmaps (aligned with renovation passports) |
| Performance assessment & management | Continuous monitoring with anomaly detection alerts |
| | Automated KPI calculation and sustainability performance assessments |
| | AI-driven proposals for performance optimization measures |
| Asset management | Automated scenario analyses for asset strategies |
| | Identification of value enhancement opportunities |
| Legal compliance, financing & insurance | Automated collection and validation of compliance-related data points |

| | |
|---|---|
| | Automated generation of regulatory and risk assessment documents |
| Valuation | Identification of value-influencing building properties and quantification of impact |
| | Automated property valuation models |
| Marketing | Automated selection of key building attributes for marketing materials |
| | Dynamic generation of real estate brochures |

The practical realization of the proposed functions depends on various factors, particularly the availability and quality of relevant data, as well as the economic viability of their implementation in specific use cases. However, these functions demonstrate the practical application of selected built-up functions and highlight the potential of DBPs in addressing key challenges in building-related information management.

# 7.3 Point of view: data

## 7.3.1 Derivation and assumptions

Building-related data form the backbone of DBPs, enabling essential functions such as data entry, sharing, and analytics. However, the effectiveness of a DBP depends not only on the availability of data but also on how data are structured, managed, and made accessible. Without a well-defined approach to data organization, a DBP risks becoming a fragmented repository rather than a functional system that supports decision-making and long-term usability.

The derivation of the data element for DBPs is particularly challenging due to the unique characteristics of building-related data. These include based on the insights of chapter 3:

- Multi-dimensional nature: Buildings are perceived differently depending on the perspective and use case, leading to diverse information categories and focal points.
- Static and dynamic aspects: Buildings are long-lasting products with static structures but also dynamic systems characterized by inputs and outputs, requiring data to account for both static and dynamic components.
- Modular and hierarchical structure: Buildings consist of elements and components, often associated with numerous properties. This leads to hierarchical data abstractions in data modeling.
- Complexity and system boundaries: Buildings are unique systems with multiple interfaces to their environments, requiring clear system boundaries to manage relationships within and across systems while minimizing redundancies.
- Levels of aggregation: Building-related data exist at varying levels of granularity, from individual data points to highly aggregated datasets.
- Ownership and variability: Building-related data are distributed across multiple stakeholders, stored in diverse formats and media, and varies significantly in quality.

These characteristics illustrate the challenge of establishing a unified and functional perspective on building-related data. Given the requirements on the data content and quality (sections 5.4 and 5.5), the data element of the ISA must therefore support a structure that maintains accessibility, quality, and interoperability across use cases and actors. This is primarily achieved through two tightly connected components: a *data model*, which defines the structure and semantics of the data, and an overarching *data architecture*, which organizes specifications, identifiers, and metadata to ensure consistent handling and usability.

The data model and data architecture are closely connected. As outlined in section 4.2.2, the data structure defines essential elements such as data specifications, metadata, and identification schemes, all of which enable semantic clarity and interoperability. However, instead of addressing these architectural elements in isolation, they are considered in the presentation of applicable data modeling approaches where appropriate. This is because the choice of modeling approach significantly influences how architectural elements are implemented in practice. For example, ontology-based approaches inherently support metadata, identifiers, and formal semantics, while schema-based approaches require more explicit definitions. Thus, architectural considerations are embedded in the evaluation of modeling approaches and are discussed in that context. Further technical details on the implementation of architectural components are not within the scope of this section, as this exceeds the conceptual view of the ISA.

A more detailed explanation of the core components of such a data architecture in the context of DBPs/DBLs is provided in section F.1, based on the framework proposed by Böhms et al. (2023).

### 7.3.2 Data content

The data content of a DBP is central to ensuring its capability to support life cycle-oriented tasks and meet the diverse requirements of actors. Rather than reiterating the data categories and points already discussed in the requirement profile for LC-BISs (section 5.4) and detailed in the associated appendices, this section highlights their relevance to the DBP data element. A DBP should encompass building-related data across various categories as specified in the taxonomy derived in chapter 3.3, including master data, inventory data, legal and economic data, and performance data. These data categories offer a simple yet effective way to cover all relevant building-related data points. By including raw data, aggregated indicators, documents, and metadata, DBPs serve as dynamic repositories that can bridge actor needs across life cycle stages.

For detailed insights into the specific data points and their classification, including their relevance for building life cycle tasks, readers are directed to the requirement profile (chapter 5) and to the appendix (section B.7). These provide a foundational overview, ensuring clarity on why certain data are essential and how they align with the overarching goals of life cycle building information systems.

### 7.3.3 Data modeling approaches

A data model is, as explained above, a fundamental component of the data element, as it defines how building-related data are structured, organized, and managed. It can ensure consistency, interoperability, and scalability, which are critical for addressing the diverse requirements of DBPs. While a DBP could, in its simplest form, function without a formalized data model, acting as a static repository for unstructured or semi-structured documents such as PDFs or spreadsheets, this approach has severe limitations. Without a data model, data representation would be inconsistent, interoperability with other systems would be limited, and managing data efficiently would require considerable manual effort. These constraints make such an approach unsuitable for more complex use cases, such as integrating multiple data sources.

Given the potential importance of a structured approach, it is worth exploring whether existing data modeling frameworks from subdomains and related BISs could address the needs of DBPs. Leveraging these frameworks could simplify the development process while ensuring the seamless integration and management of building-related data. Data modeling frameworks include:

- Standards for building-related data exchange and sharing from initiatives in the real estate industry and from standardization bodies with the goal to establish an industry-wide data model, such as the standards from IBPDI, OSCRE, or RICS
- Data models that were originally designed for a specific subdomain within the building life cycle, but that gradually evolved to a more comprehensive approach, such as the IFC data standard
- Data models that show significant potential to meet relevant data quality requirements (section 5.5), such as data availability or interoperability, based on the implemented data modeling approach and language (e.g. ontology-based approaches with linked data), such as RealEstateCore's ontology or the Brick schema
- Data models specifically proposed or implemented for DBPs and DBLs, such as the semantic data model proposed by the EC

A specific selection of data standards that fit into either of these categories was analyzed to evaluate their potential, focusing on their primary advantages and disadvantages (section F.2). This analysis included four ontology-based standards, one dictionary-based standard, three standards utilizing data formats such as JSON and XML, one IFC-based standard, and one without a specific data format. The findings indicated no standout potentials and limitations that were specific to only one of the models. Differences rather derived from the data modeling approach that was applied. Consequently, a detailed comparison of the different types of data modeling approaches was conducted, providing insights into how effectively they address the requirements for data content and quality in DBPs (Table 7.4). In addition to the modeling approaches analyzed, a basic scenario was added, assuming a hierarchical data modeling approach based on the taxonomy of building-related data needs.

Table 7.4: Overview of different data modeling approaches for digital building passports

| Data modeling approach | Strengths | Weaknesses |
| --- | --- | --- |
| Taxonomy- / hierarchy-based modeling | Provides a structured and easily understandable classification of data;<br>Supports hierarchical relationships that reflect real-world building structures;<br>Well-suited for predefined and stable data categories | Limited ability to represent complex, cross-cutting relationships;<br>Lacks semantic richness, making interoperability and data integration challenging;<br>Does not inherently support extensibility for evolving data needs |
| Ontology-based semantic modeling | High level of semantic data interoperability;<br>Well-suited for (knowledge) graphs;<br>Strong basis for data analytics (e.g., AI applications);<br>Independent of physical data modeling and storage;<br>Can represent semi-structured and unstructured data | Matching different ontologies can be challenging;<br>Broader scope may result in less detailed properties;<br>Difficult to represent building geometries effectively |
| Combination of ontologies and data dictionaries | Standardizes terms and concepts;<br>Leverages the strengths of ontology-based approaches;<br>Enhances semantic clarity while maintaining operational focus | Inherits weaknesses of ontology-based approaches;<br>Requires alignment between ontologies and dictionaries to avoid conflicts |
| Integration of semantic and logical modeling through specific data schemas/formats (e.g., XML, JSON) | Combines semantic and logical approaches for efficiency;<br>Provides unambiguous formalization through schemas and formats;<br>Well-suited for structured data and hierarchical relationships | Reduced interoperability with systems using different schemas;<br>High manual effort for updates or schema changes;<br>Changes to the physical level can introduce inconsistencies;<br>Not suitable for unstructured data |
| Schema-based modeling with IFC | Established domain standard for interoperability;<br>Rich semantic modeling of building-related data, including geometry and relationships;<br>Broad industry adoption;<br>Compatibility with BIM tools and workflows | Complexity of schema makes implementation challenging;<br>Limited flexibility for use cases beyond the BIM domain;<br>Requires expertise to adapt for specific applications |

The general trend in data modeling for DBPs favors ontology-based approaches due to their advantages in semantic and technical interoperability. Ontologies represent data semantics independently of specific physical formats, offering flexibility for integrating heterogeneous data sources and supporting long-term, interoperable data management. This contrasts with schema-based approaches like IFC, which excel in formalizing structured and hierarchical data but often lack the semantic richness needed for broader interoperability. Ontologies play a crucial role in linked data approaches and semantic data models, enabling the integration of decentralized and distributed data sources. An example of such an approach, based on the RDF modeling language, is provided in section F.3.

Ontology-based approaches show their greatest potential when combined with data dictionaries. Dictionaries provide standardized vocabularies that ensure consistency and reduce ambiguity, complementing the semantic richness of ontologies. Together, they create a framework capable of addressing both complexity and precision, making them particularly advantageous in multi-stakeholder environments where clarity and interoperability are essential.

Despite their promise, ontology-based approaches are still relatively new in the real estate domain and have not yet reached the maturity of standards like IFC. IFC remains a robust option, particularly for use cases requiring detailed representations of geometry and relationships, benefiting from industry adoption and BIM tool support. However, its complexity and reliance on specific formats can limit accessibility for users outside traditional BIM workflows.

For some use cases with lower requirements on scalability and semantic richness, a taxonomy-based modeling approach may be sufficient. This applies especially when handling data and documents that are not strictly adhering to the data model, as a hierarchical structure can still provide clear classification and organization. While it lacks the flexibility and interoperability of more advanced semantic approaches, its structured simplicity makes it a viable option for specific DBP applications.

From the authors' perspective, ontology-based approaches, especially when combined with data dictionaries, offer the greatest functionality for DBPs by ensuring semantic clarity, interoperability, and adaptability. The potential future role of RDF-based modeling is particularly noteworthy here, as it provides a robust foundation for linked data and semantic web technologies. However, no single approach can be prescribed for all use cases. Rather than defining a universal standard, it is recommended to first establish clear requirements, particularly regarding data content, as outlined in the requirement profile, and then select a suitable data modeling approach accordingly. This ensures that the chosen model aligns with the specific needs of actors, use cases, and system functionality, rather than imposing unnecessary complexity or limitations.

The adaptability of an ontology for DBPs is well illustrated by the proposal from Böhms et al. (2023) for a semantic data model (section F.3). This model incorporates some of the latest research in the context of DBPs and DBLs and is grounded in a comprehensive data architecture framework.

## 7.4 Point of view: users

### 7.4.1 Derivation and assumptions

The user element within a DBP must provide comprehensive support for the various actors interacting with the system. These actors, such as building owners, tenants, service providers, and regulatory bodies, each possess distinct roles, levels of expertise, and varying preferences in how they engage with the system. The diversity in these roles, along with differences in expertise and motivations, introduces complexity in managing user access and interactions with the DBP. The system must be capable of handling this diversity, ensuring that each user can effectively navigate the DBP according to their specific needs and responsibilities.

An essential assumption is that the user element must be designed to accommodate varying levels of control, support, automation, and visualization preferences across different actors. For instance, a building owner might require more comprehensive control over data and functions, while a service provider might need automated workflows and real-time data. The system must allow for such differentiation while ensuring smooth integration with other system components.

Additionally, the user element must support the overarching functionality of the system. It must contribute to the preservation of data quality and uphold key system-related requirements, including data security and privacy. A core challenge lies in balancing the need for personalized user experiences with the necessity of adhering to data governance standards. On one hand, the system must have access to certain user information to optimize functionality, such as enhancing personalization and supporting role-based access controls. On the other hand, it must limit the scope of information gathered to comply with data privacy laws and ensure the protection of sensitive data.

This interplay between user-specific needs and data governance underscores the importance of a robust user model. The user model must not only accommodate the complexity of different users and their evolving needs but also ensure that data access and management are done in a secure, compliant, and efficient manner. Such a model serves as the foundation for IAM, ensuring appropriate permissions and access rights for all actors involved.

In addition, a data ownership model is needed to regulate how users manage and control data within the DBP. While the user model defines access and permissions, the data ownership model establishes ownership structures, delegated rights, and data-sharing rules. As it involves both user-specific rights and data governance, it spans both the user and data view.

### 7.4.2 User model

A structured user model is essential for managing interactions within a DBP. Since an actor's perspective and tasks influence their information needs and system interactions, the model must incorporate these aspects along with the organizational context in which users operate. This ensures that different actors, such as building owners, service providers, and regulatory bodies, can effectively engage with the system according to their roles and responsibilities.

To address this, the following attributes are integrated into a proposal for a user model:

- Personal information (e.g., name, birth date) for authentication, identification, and user profile management
- Preferences and functional requirements that indicate which system functions a user needs access to
- Documentation of user actions to ensure accountability, traceability, and non-repudiation of data
- Assigned roles that determine both access rights and responsibilities within the system

The model, represented in Figure 7.5, takes a conceptual and scalable approach that allows for adaptations according to specific implementation scenarios. Instead of prescribing a rigid structure, it establishes a flexible foundation that can be expanded as system requirements evolve.

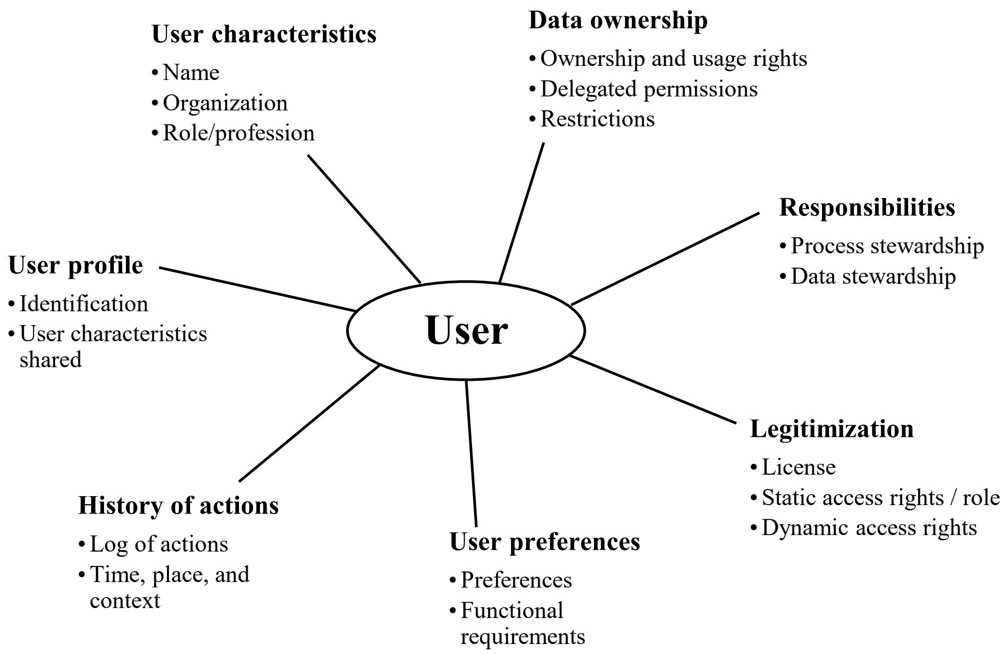



Figure 7.5: User model for digital building passports based on Buchholz and Lützkendorf (2024, p. 7)

A distinction is made between individual user models and reference user models. The individual user model represents a specific system user by integrating personal attributes, preferences, and assigned roles. These profiles enable personalized system interactions, improving usability and access management. In contrast, a reference user model serves as a general template for defining user categories (e.g., building owners, facility managers, service providers). This structure facilitates scalability by organizing access rights based on predefined roles while still allowing customization for specific cases.

A further differentiation is required between industry roles (e.g., facility manager, tenant, service provider) and system roles (e.g., administrator, read-only user). These roles must remain distinct, as an actor's professional function does not directly determine system access rights. The model must support flexible assignment of system roles while ensuring that access rights align with governance requirements.

To maintain data integrity and security, the model incorporates user action tracking, ensuring that essential system interactions (e.g., data modifications, approvals, or access requests) are logged for accountability. This tracking enables:

- Traceability of changes, allowing system administrators to monitor security-critical actions.
- Non-repudiation, ensuring that actions performed within the system are verifiable.
- Compliance with legal and governance requirements, ensuring an auditable history of user interactions.

Tracking is limited to necessary functions and must align with data protection regulations, ensuring transparency, controlled access, and appropriate safeguards for user privacy.

Finally, while the user model is primarily concerned with the management of individual users, the connections to system functions, data, and ICT elements, which are crucial for supporting user interactions, belong within the process element of the ISA. Therefore, the user model focuses on the internal representation of users, their profiles, and responsibilities, leaving the broader connections to the system's other elements to be managed by the process element.

The structure of the user model is conceptual and flexible. It provides a framework for defining individual user profiles and roles, while leaving room for future adaptations and extensions.

### 7.4.3 Identity and access management

The user model defined in the previous section provides the foundation for an IAM strategy by structuring roles, responsibilities, and user attributes within a DBP. IAM operationalizes this model by specifying access policies that regulate how actors interact with system functions and data. A structured approach to IAM ensures that users can only access the functions and data relevant to their role, balancing security with usability.

A Role-Based Access Control (RBAC) model serves as a foundational approach, assigning users to predefined roles based on attributes from the user model. This simplifies access management by ensuring that permissions are role-driven rather than individually assigned. Initially, static role assignments are preferable for managing access control efficiently. However, as system complexity increases, dynamic access controls can be introduced to accommodate evolving requirements.

A key consideration is that actors in the real estate industry often take on multiple roles across different DBPs (Table 7.5). For example, a building owner may be both a data owner and a user of a DBP, especially in cases where they self-occupy or manage multiple properties. Additionally, building owners may act as administrators of their own DBP system or request access to external DBPs where they do not hold ownership rights. These variations highlight the need for a flexible user model that can accommodate multiple role assignments.

Table 7.5: Roles in developing and using digital building passports compared to roles in the real estate industry

| Role in the DBP | Role in the real world (real estate industry) |
|---|---|
| Developer | Software developer, large real estate companies |
| Data owner | Building owner, tenant, public authority, third-party data provider |
| Administrator | (IT) service provider, building owner |
| Contractor / steward (information manager) | Service provider, building owner |
| User | Building owner, stakeholders of the real estate industry |

RBAC assigns data access permissions based on role categories, ensuring that different levels of data sensitivity are protected. Access rights can be distinguished between data insight (read access) and data interaction (edit access) (section 7.2.2). Since data ownership plays a critical role in IAM, data owners must retain control over their data, including the ability to define access and usage permissions for others.

Table 7.6: Access rights for roles in a digital building passport

| | **Data insight** | | | **Data interaction** | | |
|---|---|---|---|---|---|---|
| | Private data | Shared data | Public data | Restricted data | Shared data | Public data |
| **Data owner / provider** | x | x | x | x | x | x |
| **Data user / consumer** | | (x) | x | | | |
| **Data steward** | (x) | (x) | x | (x) | (x) | x |

x: full access, (x): conditional access, blank: no access

While RBAC provides structured access control, it may be insufficient in scenarios where more granular, context-aware permissions are required. A hybrid approach that integrates Attribute-Based Access Control (ABAC) can provide additional flexibility. In ABAC, access is determined based on user attributes, system objects, and contextual conditions rather than just predefined roles. This approach is particularly beneficial in dynamic use cases, such as:

- Temporary project-based access: A contractor may be granted access to maintenance records only for the duration of a refurbishment project, after which access is automatically revoked.
- Life cycle-based access control: A regulatory body might be given access to compliance documentation only during the construction phase, but not during the operational phase.

As the number of subjects (users), objects (functions), and environmental states (contextual conditions) increases within a DBP, ABAC becomes more favorable due to its ability to manage complex access control requirements. In this model, subjects refer to users, objects refer to system functions, and environmental states refer to external factors influencing access (section F.4.1).

Beyond RBAC and ABAC, Discretionary Access Control (DAC) can further refine access management by allowing data owners to make context-specific decisions about data sharing. DAC is particularly useful in collaborative scenarios, where access permissions are not preconfigured but instead granted on a case-by-case basis. For example:

- A building owner grants access to certain energy data only for a specific tenant.
- A facility manager shares maintenance logs with a service provider for a limited period.
- A public authority is granted temporary access to fire safety documentation during an inspection but loses access once the process is complete.

The choice of an IAM strategy depends on the context and complexity of the DBP implementation. For DBPs in large buildings or portfolios where multiple actors interact with different levels of permissions, ABAC can provide the necessary flexibility and precision. However, in simpler use cases, such as a single-owner DBP with limited external interactions, RBAC may be sufficient. In any case, RBAC should serve as the foundation due to its intuitiveness for most actors and ease of implementation. By integrating RBAC, ABAC, and DAC, the IAM strategy ensures efficient access management while balancing usability, security, and flexibility.

### 7.4.4 Data ownership management

The proposed data ownership strategy for DBPs builds on a decentralized ownership model, recognizing that data are generated, used, and reused by various actors across the building life cycle (section 4.6.2). Rather than assigning exclusive control to a single entity, this approach ensures that actors retain sovereignty over the data they contribute, while also enabling delegated control, co-ownership, and structured sharing. This reflects the complexity of ownership in real-world BISs, where overlapping claims, fragmented systems, and dynamic project roles require flexible yet robust governance mechanisms.

While legal ownership of data is not always clearly defined, the right to control and manage data is crucial for ensuring transparency, security, and usability in a multi-actor environment. To support this, DBPs must provide mechanisms to:

- Define who can access, manage, and modify data, regardless of legal ambiguities;
- Support collaboration by clearly regulating shared control and co-ownership;
- Ensure accountability through contractual agreements that clarify responsibilities and delegation rules.

To implement this strategy, the following principles apply:

- Full control by data owners: Data contributors maintain the ability to define access, delegate control, and manage usage permissions;
- Delegation of data control: Data owners may authorize stewards (e.g., contractors, facility managers) to manage data on their behalf, without relinquishing ultimate control;
- Co-ownership and shared control: When multiple actors contribute to a dataset, agreements must specify roles, responsibilities, and access rights;

- Ownership transfer considerations: When data responsibility shifts, for example, during a building sale or transition from construction to operation, DBPs must support seamless handovers by allowing ownership and control rights to be reassigned in a transparent and traceable way.

The decentralized approach enables autonomy for each data owner while preserving accountability and governance. It fosters data sharing without centralizing control, which is essential in fragmented and collaborative environments such as real estate projects. To operationalize this model, IAM, metadata tracking, and formal agreements play key roles. Where multiple actors contribute to a dataset, federated structures or delegated stewardship help ensure that shared control remains transparent and manageable.

## 7.5 Point of view: technology

### 7.5.1 Derivation and assumptions

The technological view within the ISA for DBPs outlines the role of ICT in managing digital data throughout the building lifecycle. ICT serves as the non-human component that supports all elements of the system, from conceptual models to physical implementations. Identifying relevant ICT components for DBPs requires understanding their role in specific function bundles, such as data collection and process automation.

ICT can be classified into core technologies and technologies for additional support and automation. Core technologies ensure the system's fundamental operations, while advanced technologies enhance system capabilities, improving efficiency and automating processes.

The technologies discussed are based on insights from chapter 4 on ICT's impact on building-related data management. The selection of technologies reflects their potential for DBPs, and their integration into a holistic system is what sets DBPs apart.

System requirements such as availability, efficiency, and scalability can influence the choice of technologies that may support DBPs in remaining functional, cost-effective, and adaptable. Core technologies like cloud platforms and fault-tolerant systems could contribute to ensuring availability, while modular designs and microservices might support scalability. Advanced technologies such as AI-driven analytics and automation could enhance efficiency and optimize building operations. The flexibility of APIs and the security offered by blockchain, alongside traditional data protection measures, can potentially aid in ensuring the system's configurability and trustworthiness.

The technologies selected are not only necessary for fulfilling the functional requirements of DBPs but also provide a foundation for further development and adaptation to specific use cases. It is important to emphasize that the technologies described here are conceptual suggestions derived from current potentials and system requirements. Their inclusion does not imply a prescriptive implementation path. In fact, technological neutrality is essential to ensure interoperability, long-term adaptability, and to avoid lock-in effects that could limit future development or vendor independence. The focus should always remain on fulfilling the relevant functions and requirements of DBPs: Technology serves these goals, not the other way around.

## 7.5.2 Core technologies

### 7.5.2.1 Information infrastructure

For the successful implementation of DBPs, core technologies are essential to ensuring the system's functionality, usability, and data quality, as outlined in the requirement profile (chapter 5). These technologies include critical infrastructure, hardware, and software, which are necessary to meet minimum system requirements.

Access to core technologies can vary significantly depending on the region and the resources available to actors in the real estate industry. While DBPs can function with minimal features, their potential is most significant in regions with well-established infrastructure and where actors have the resources to procure necessary technologies. Specifically:

- Critical infrastructure such as stable power supply, telecommunication networks, and reliable internet access is foundational for DBPs, particularly in supporting data interaction and cloud-based services.
- Hardware such as computers, smartphones, and smart devices enables users to interact with the system, while specialized hardware may be required to support data collection or system monitoring.

These elements are particularly relevant in developed and developing countries, where access to infrastructure directly impacts the feasibility and effectiveness of DBP implementation. The infrastructure requirements should be carefully considered for each context to ensure successful deployment.

### 7.5.2.2 Cloud architecture

The proposed three-layer architecture for DBPs, comprising presentation, application, and data management layers, serves as the backbone of the system's design. This architecture is critical because it allows for clear separation of concerns, ensuring flexibility, scalability, and easier maintenance of the system. The reasoning behind this structure is that it facilitates the modularity of the system, making it easier to adapt to evolving needs in real estate management. Data can flow seamlessly between layers, providing efficient access and management for users.

In this model:

- The presentation layer handles user interactions through a user-friendly interface, which is crucial for non-expert users in the real estate industry. The interface must be intuitive, accessible across devices (computers, smartphones, tablets), and adaptable to various web browsers, ensuring broad compatibility and ease of use.
- The application layer acts as the intermediary between the user interface and the data management layer, processing core system functions through modular components. This modular approach enables greater flexibility, scalability, and maintainability by dividing

the system into distinct, independent units that can be developed, deployed, and modified separately. This modular structure can be achieved using microservices (section 7.5.3.1).

- The data management layer stores and retrieves data, ensuring that information is organized, structured, and accessible. A DBMS is required to manage this layer, facilitating the transformation of semantic data models into logical and physical data models depending on the type of database used. Relational databases are ideal for structured data, while graph databases support linked data models, which are particularly suited for heterogeneous and interconnected data.

Cloud-based deployment through Infrastructure as a Service (IaaS) is particularly beneficial for DBPs because it allows for distributed, scalable, and cost-efficient data storage and computation. The cloud offers flexibility in terms of resource allocation, reducing the need for expensive on-site infrastructure and allowing for better management of large datasets and real-time processing requirements.

For ease of application development, cloud development platforms like low-code/no-code tools enable faster deployment of applications. These platforms simplify backend integration, user interface creation, and the management of cloud resources, allowing developers to focus on core system functions without extensive coding.

#### 7.5.2.3 Data security technology

Data security is a critical element of DBP architecture, ensuring that sensitive building-related data are protected against unauthorized access, tampering, and loss. Given the variety of data types handled by DBPs, including personal, technical, and financial information, robust security measures are essential for maintaining the integrity, confidentiality, and availability of these data.

DBPs serve as repositories and management tools for comprehensive building data, often involving multiple actors across the building life cycle, such as owners, facility managers, contractors, and regulators. Therefore, ensuring that data are secure from external threats and internal mishandling is paramount to the trust and usability of the system. To achieve this, the proposed security technologies are integrated at multiple levels of the DBP architecture, ensuring that security is embedded throughout the system rather than treated as an afterthought.

The following security measures are crucial for DBPs:

- *Access control*: DBPs must implement robust access control mechanisms to regulate who can interact with different data types and system functions. RBAC/ABAC models should be employed to grant access based on the user's role or specific attributes (section 7.4.3). This ensures that only authorized users can access or modify sensitive data, aligning with DBPs' goal of empowering different actors with controlled access while protecting critical information.
- *Data encryption*: Encryption should be employed both for data at rest (stored data) and data in transit (data being transferred between layers or to external systems). This ensures that even if data are intercepted or accessed by unauthorized parties, they remain unreadable. Given the sensitive nature of selected building-related data, encryption is fundamental for protecting this information during both storage and communication.

- *Secure development practices*: Security vulnerabilities can arise from the development process itself. Therefore, secure coding practices must be followed to mitigate risks from common exploits. Adopting secure development frameworks and regular security audits during the development phase of DBPs ensures that the system is resilient against common threats, particularly those targeting web applications.
- *Data backup and recovery*: A reliable backup strategy is essential for data integrity. For DBPs, data backups must be created regularly to prevent loss in the event of system failure, accidental deletion, or data corruption. Moreover, backups should be geographically distributed to mitigate risks from localized disasters, ensuring that building-related data can be restored quickly without compromising security or accessibility. One advanced option is provided by **blockchain technology**, which can create immutable data logs and ensure traceability (section 7.5.3.3).
- *Audit and monitoring*: Continuous monitoring of system activities and regular audits are necessary to detect potential breaches, unauthorized access attempts, or anomalies. By logging access attempts and changes to critical data, DBPs can maintain an audit trail that not only supports operational transparency but also provides a crucial layer of security. This is particularly relevant for DBPs, as different actors will be interacting with the system and data at various stages of the building life cycle.

The proposed data security measures are crucial for ensuring that DBPs maintain trustworthiness, integrity, and availability while effectively managing complex building-related data across all layers of the system.

## 7.5.3 Additional support and automation

DBPs offer numerous opportunities to integrate additional technologies that, while not essential for core system functions, significantly enhance the overall system functionality. These technologies can automate manual processes, reduce user workload, improve efficiency, and enable new possibilities for information management. Notably, automation is valuable for addressing upstream and downstream processes, such as data collection and analytics. While these technologies are not inherently part of DBPs, they can play a crucial role when applied at the right stages throughout the building life cycle.

### 7.5.3.1 Microservices

Microservices are a highly flexible and scalable architectural approach that can play a significant role in DBPs, especially as the system grows in complexity and functionality. By dividing the system into smaller, independent services, microservices allow DBPs to modularize functions, which improves flexibility, scalability, and maintainability. Each microservice can be developed, deployed, and scaled nearly independently, making the system more adaptable to changing requirements and future growth.

In a DBP, microservices could be used to handle built-up system functions for specific use cases, such as predictive analytics approaches or automated performance assessments. This modularization is particularly valuable when DBPs are expected to support a variety of actors and functions, allowing each service to evolve without impacting others. Additionally, microservices enable better maintenance, as updates or changes to one service do not require a complete overhaul of the entire system.

Containerization, commonly used with microservices, allows these services to run as logical packages independent of the underlying infrastructure. This adds further flexibility and simplifies deployment, especially in cloud environments. Containerized microservices can scale up or down easily based on demand, which is crucial for handling varying loads and ensuring efficient resource allocation.

#### 7.5.3.2 Linked data and semantic web technology

As already laid out in the data element, linked data can play a crucial role in improving data interoperability within DBPs. Linked data can be integrated with semantic web technologies, but this integration is not strictly necessary for all implementations. While semantic web technologies, including the use of RDF for data modeling, provide a robust framework for defining relationships between data points, linked data can also function independently, allowing for simpler data connections when a more lightweight approach is sufficient.

When implemented together, linked data and semantic web technologies enable ontology-based semantic modeling, which structures data and their relationships in a way that enhances data accessibility and query capabilities across different systems. This integration supports more meaningful and flexible interactions with diverse data sources.

The use of linked data should be considered for DBPs designed to support multiple actors and complex data integrations, especially when external systems or platforms need to be connected. In this context, linked data can also serve as a key enabler of decentralized data storage and management, supporting the decentralized data ownership model proposed for DBPs. By allowing data to remain under the control of its respective owners while still being queryable and linkable across systems, linked data helps maintain data sovereignty without sacrificing interoperability.

If the DBP remains a closed system with limited interaction, the added complexity of linked data and semantic web technologies may not be necessary. However, for DBPs aiming for broad collaboration or future interoperability, these technologies offer significant long-term benefits.

#### 7.5.3.3 Blockchain technology

Blockchain technology offers a promising method for enhancing data integrity and traceability within DBPs. By providing an immutable ledger, blockchain ensures that critical data, such as transaction history, ownership records, or maintenance logs, remain tamper-proof and verifiable. This is particularly valuable for DBPs, where transparency, data authenticity, and security are essential.

In terms of integration into the DBP architecture, a blockchain would likely be integrated into the physical data layer. It would serve as an additional layer for storing and verifying key data, ensuring that once data are recorded, it cannot be altered without traceability. Blockchain can complement traditional data storage solutions, such as relational or graph databases, by offering an immutable, decentralized record for particularly sensitive information. This would make the system more secure by preventing unauthorized modifications while maintaining a transparent and auditable data trail.

While blockchain adds significant security benefits, its integration should be targeted to areas where data integrity is of paramount importance, such as transaction logs or historical data, rather than across the entire system. By focusing its use in specific parts of the DBP data architecture, blockchain can provide value without unnecessarily complicating the overall system.

#### 7.5.3.4 Application programming interfaces

APIs are essential for data integration and interoperability within DBPs. They enable communication between DBPs and external systems, such as other BISs, including BAMSs and virtual building models, for example. APIs allow for structured, standardized data exchange, making it easier for DBPs to access external data sources and integrate with third-party systems.

Implementing APIs requires clear definitions for data formats, secure access protocols, and ongoing system management. While it requires initial effort to develop and maintain, APIs offer significant benefits in terms of scalability, flexibility, and easier integration with a broad range of external systems. APIs also facilitate modularity, enabling DBPs to expand their functionality over time without overhauling the core system.

In comparison to linked data, APIs provide a more direct and structured approach to data exchange, where specific endpoints allow for precise interactions between systems. Linked data, on the other hand, enables dynamic, context-driven connections between data across systems. Both technologies support integration with external systems, but APIs are ideal for well-defined, structured exchanges, while linked data excels in linking heterogeneous data sources in a more flexible manner.

#### 7.5.3.5 Artificial intelligence for data collection

AI technologies, particularly ML and computer vision, are crucial for secondary data collection within DBPs, especially when integrating existing data sources into the system. AI can assist in digitizing building-related data, such as scanned documents or blueprints, using technologies like OCR, 3D model recreation, and computer vision. These AI-powered techniques automate the extraction and classification of data, enabling DBPs to process and incorporate historical or unstructured data into their databases.

While original data collection (e.g., geometric data from laser scanning or surveys) is not inherently part of DBP functionality, AI can play a role in enhancing the integration of geometric data into the system when it's gathered. AI can help automate the processing and interpretation of these data, reducing the need for manual input and ensuring that DBPs remain accurate and up-to-date.

Additionally, for sensor-based data collected via BAMSs, AI technologies can assist in processing and analyzing real-time data from IoT devices and sensors, which can then be integrated into the DBP. This enables ongoing monitoring, predictive maintenance, and dynamic adjustments, enhancing the DBP's ability to provide actionable insights throughout the building life cycle.

#### 7.5.3.6 Artificial intelligence for data analytics

AI-driven data analytics enhances the efficiency and automation of DBPs by enabling advanced data processing, pattern recognition, and decision support. Given the large volume and complexity of building-related data, AI can support automated insights and process optimization in various DBP functions:

- AI should be used to automate data-driven processes that require real-time analysis, such as anomaly detection, predictive maintenance, and performance optimization.
- AI should complement structured analytics functions (as outlined in section 7.2.3), ensuring that results remain interpretable and actionable for DBP users.
- The integration of AI should be tailored to data availability and business needs, allowing for scalable implementation depending on system complexity and user requirements.

To effectively incorporate AI, DBPs require a robust data management and computational framework that supports AI processing. AI integration can be facilitated through:

- Cloud-based analytics services for scalable data processing and machine learning model deployment.
- Edge computing for localized, real-time analytics where immediate responses are required (e.g., automated building control).
- Data structuring techniques to ensure AI can efficiently extract meaningful insights from heterogeneous building-related datasets.

By strategically integrating AI within DBPs, data analytics capabilities can be expanded without increasing complexity for users, ensuring reliable, automated insights that enhance decision-making and operational efficiency.

### 7.5.4 Summary and technology combinations

Technologies reach their full potential when used in combination, creating synergy effects that enhance the overall functionality of DBPs. By integrating core technologies in a standardized structure, DBPs ensure that they meet essential system requirements, such as scalability, data security, and interoperability. The choice of additional technologies, such as AI, Linked Data, and blockchain, depends on the specific use case and should be built around the core structure according to the system's needs. It is crucial that requirements are specified first, as they form the foundation for selecting appropriate technologies. This combination of core and additional technologies enables DBPs to evolve and adapt to changing requirements, while minimizing the limitations of individual technologies.

Figure 7.6 illustrates the relevant ICTs for DBP as laid out in this section. It integrates the different technologies in the three-layer architecture that was proposed, thus enabling a modular and scalable employment of their functionality.

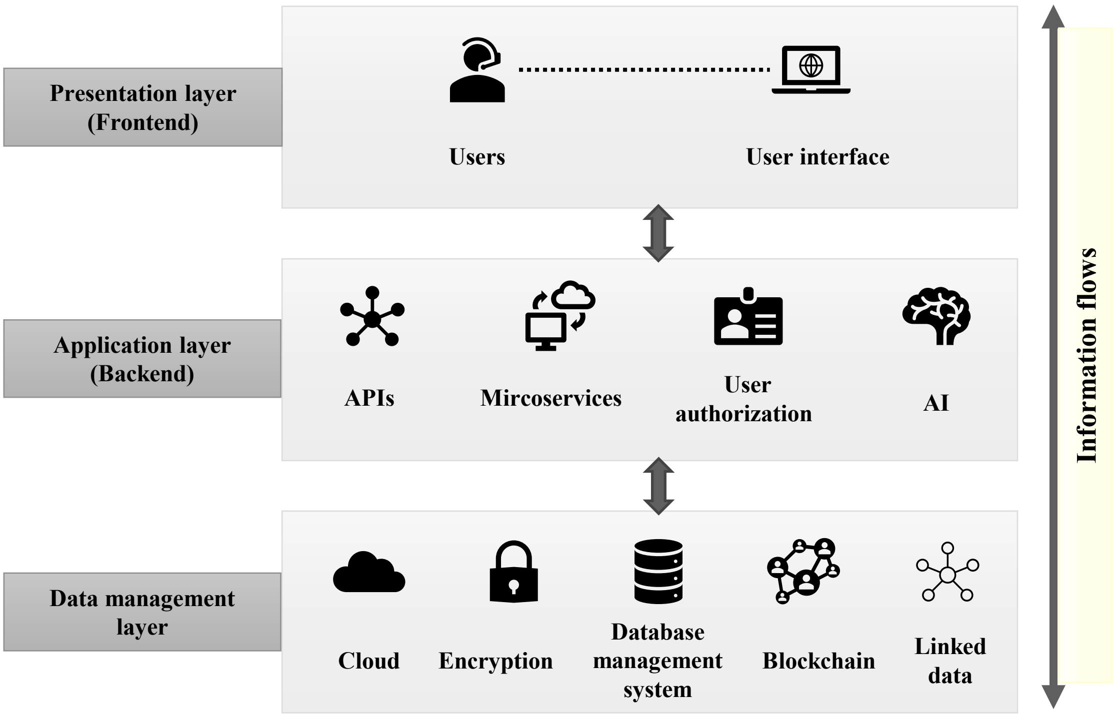



Figure 7.6: Overview on relevant technologies for digital building passports

# 7.6 Point of view: processes

## 7.6.1 Derivation and assumptions

The process element serves as the core of the ISA, as it dynamically connects and integrates all other elements within a coherent framework. Unlike the static perspectives of the function, user, data, and technology views, the process view incorporates the dimension of time, enabling the flow of resources, primarily information, between the system's elements and its environment. This dynamic interplay is crucial for ensuring that DBPs function effectively as adaptive and integrated systems.

- Information flows between the ISA elements: These bidirectional flows link the static elements of the ISA (e.g., user, data, function, and technology) with the dynamic process element. This integration not only ensures that processes reflect and adapt to changes within the static elements but also facilitates updates to those elements through the process framework.
- Information flows within the process element: Internal information flows connect the procedural steps and entities involved in DBP processes. These processes generally follow a circular lifecycle comprising three stages: Initialization, triggered by specific events, such as user actions or system events, execution, the main stage where procedural steps are carried out, utilizing system resources to achieve specific outcomes, finalization, marking the end of a process while preparing the system for the next cycle. Changes to the static

elements are implemented during the process life cycle, while the process element itself reverts to its initial state, making it inherently reversible and cyclical.

- Information and resource flows between the system and its environment: External flows involve the exchange of resources, including actors, data, and ICT, between the DBP and its surrounding environment. Inputs, such as commands, data integrations, or system resources, are processed within the DBP, and outputs, such as processed data or actionable insights, are delivered back to the environment. This bi-directional exchange allows DBPs to integrate seamlessly with their environment, including other BISs. For example, a user may input data as commands or queries, while the system provides corresponding functionalities and outputs.

Based on these considerations, two fundamental requirements emerge for the process element:

- Internal integration: Ensuring seamless interactions among ISA elements within the process framework
- External interaction: Managing robust exchanges between the DBP and other established BISs, particularly in the context of existing systems and integration challenges.

By addressing these flows and their respective requirements, the process view lays the foundation for a comprehensive and adaptable DBP system.

### 7.6.2 Internal information flows

The elements of the ISA have so far been treated as static and independent to reduce system complexity. The process view now serves to bring these elements back together in an integrated framework, illustrating how the system functions dynamically by representing interactions between elements and between the system and its environment. While this integration significantly increases complexity, a step-by-step approach can manage it effectively.

A practical strategy to handle this complexity involves analyzing binary relationships between two elements at a time before layering additional elements and interactions. Table 7.7 outlines key connections between ISA elements that require further clarification.

Table 7.7: Binary relations between elements of the information system architecture for digital building passports based on Buchholz and Lützkendorf (2024, p. 12)

| Elements | Function | Data | Technology |
|---|---|---|---|
| User | Specification of rules for the chosen access policy<br>Requires information on requirements and occasions of BP use | Complex many-to-many relation on an abstract level that needs to be specified on a more detailed level | Specification of technology for user management |
| Function | | Complex many-to-many relation on an abstract level that needs to be specified on a more detailed level | Specification of technologies needed/beneficial for functions |
| Data | | | Specification of technology for data architecture |

As these binary relationships are established, they serve as the basis for understanding more intricate workflows involving multiple elements. For instance, a user accessing a function might trigger a chain of actions: retrieving data from the system, processing it through specific technologies, and delivering the desired output. The process element orchestrates these interactions, ensuring that workflows operate smoothly and adapt dynamically to changes in system requirements, user needs, or external inputs. By aligning resources and actions across the ISA elements, the process element supports a coherent and efficient integration of all system components.

To fully realize the potential of the process element, a process model is required to specify and standardize these interactions. Such a model provides clarity on how individual elements contribute to system workflows, while also offering the flexibility to adapt as the DBP evolves. By structuring processes systematically, the model enhances user guidance, supports system maintenance, and ensures that the DBP remains responsive to the diverse demands of its environment.

### 7.6.3 Job-sharing possibilities for building information systems

In order to identify relevant information flows between DBPs and other BISs, it is worthwhile to examine their differences and similarities and establish clear system boundaries. This involves addressing key questions, such as:

- How do DBPs differ in terms of data, functions, users, and ICT compared to other BISs?
- What are the primary use cases of DBPs in their role as LC-BISs compared to other BISs?
- What additional criteria for differentiation between BISs can be considered?

These questions were addressed from a neutral perspective in chapter 6. Based on this analysis, the concept of DBPs has been proposed as a suitable foundation for a LC-BIS. With the further specification of DBPs through the proposed ISA, the comparison to other BISs now requires refinement. A clear differentiation is crucial to facilitate the adoption of DBPs in the real estate industry, where a variety of BISs with established use cases and implementations already exist.

By incorporating insights from chapter 6, several functional clusters of BISs can be identified to define their relationship with DBPs. Based on the defined functionality of DBPs, several typical relations emerge, which form the basis for job-sharing approaches:

- Full integration: The DBP could take over the functions and data of this BIS completely.
- Data integration: The DBP integrates building-related data from this BIS, either through data exchange or data sharing/linking.
- Data provision: The DBP provides building-related data to this BIS, either through data exchange or data sharing/linking.
- Function provision: The DBP provides functions to this BIS beyond its role as a data repository, including data quality management, data analytics, and document generation.

The relations between different BISs and DBPs based on this classification are shown in Table 7.8.

Table 7.8: Differences between digital building passports and other building information systems including options for job-sharing

| **Type of BISs** | **Differences in information system elements** | **Options for job-sharing** | | | |
|---|---|---|---|---|---|
| | | Full integration | Data integration | Data provision | Function provision |
| **Other passports, i.e. material, renovation, product passports** | Similar tools with more specific data scope | (x) | x | (x) | |
| **Virtual building model applications** | Similarities in data scope and function, differences in technology and user groups | | x | (x) | |
| **(Corporate) real estate management systems** | Functions more task-oriented, more narrow data scope | | (x) | x | x |
| **Tools with data collection functions, e.g. BAMSs** | Slightly different functions and users, different technologies and data scope | | x | | |

| | | | | | |
|---|---|---|---|---|---|
| **Task-specific tools with data needs, such as building registers** | Overall different tools, but overlaps in data scope | | | x | |
| **(Sustainability) assessment tools** | Different functions, but similarities in data scope | (x) | x | x | x |

The type of job-sharing between DBPs and other BISs is not solely determined by their functional differences but also by the timing of their creation and usage. The direction of information flow between systems may shift over time, depending on their role within the building life cycle. For instance, real estate management systems can serve as an initial information source for DBPs during their setup phase, providing key building-related data collected over time. However, as the DBP becomes the central repository for structured building information, the flow of data reverses, with DBPs supplying up-to-date information back to real estate management systems.

The relations shown in Table 7.8 highlight the potential of DBPs as a central interface within a modular BIS ecosystem, facilitating data availability and sharing across systems. A conceptual view on this interface character was first proposed in a publication by the author (section F.5). By aggregating building-related data from data-collecting systems like BAMSs, DBPs provide structured information to actors across the building life cycle and to higher-level systems such as real estate management tools. This enables vertical integration.

In addition, DBPs should connect with other BISs that carry out similar functions, including topical passport schemes such as material or renovation passports. These systems can be fully integrated into a DBP, particularly as the material composition of a building and renovation information align closely with the DBP's data scope. This integration could simplify information management by reducing administrative effort and the need to operate multiple independent BISs. At a minimum, building-related data relevant to both systems should be made available through interfaces or linkages.

On a horizontal level, virtual building models and DBPs should be interconnected to enhance data accessibility and usability. Virtual building models, based on BIM and digital twins, offer advanced visualization capabilities for building geometry and facilitate digital design, construction, and management. They also provide a computational environment for data analytics to support decision-making processes. However, the use of BIM models and digital twins often requires specialized expertise, prior knowledge, and significant setup costs. In contrast, DBPs are designed for a broader audience with varying levels of expertise (section 6.6). Therefore, interlinking these systems, for example, through a common data model or APIs, is only relevant when both types of systems are in use. In the future, full integration of DBPs and virtual building models could be feasible, provided that critical user requirements are met.

Figure 7.7 illustrates the placement of DBPs in the landscape of important BISs, demonstrating how information can be integrated vertically and horizontally in proximity to a building.

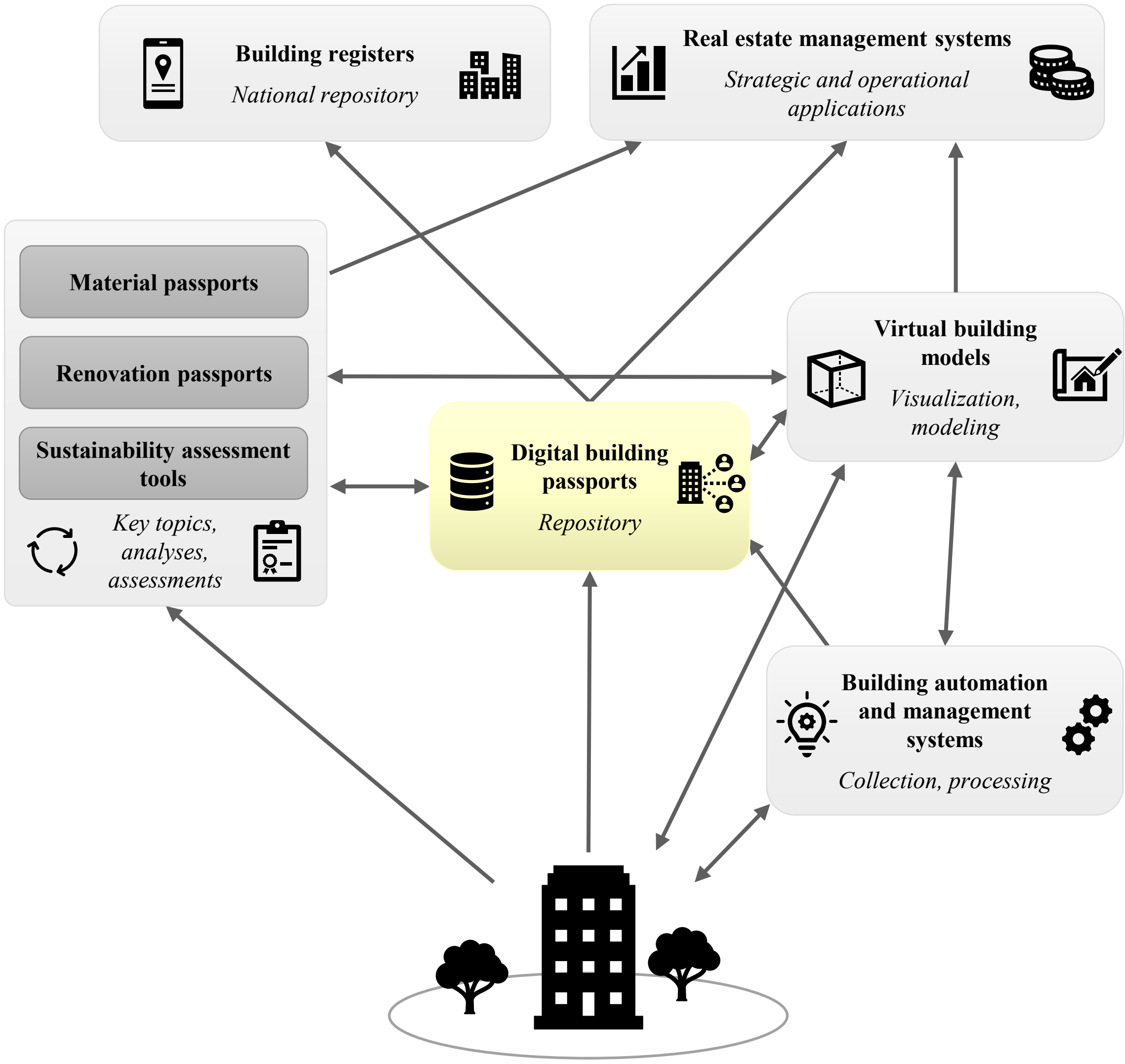



Figure 7.7: Ecosystem of building information systems including mutual interactions with digital building passports based on Buchholz and Lützkendorf (2024, p. 5)

To fulfill their role as an interface within a modular BIS ecosystem, DBPs require robust technical solutions to support the job-sharing approaches described above. Data integration, for example, involves aligning external data structures with the DBP's data model, ensuring metadata compatibility and maintaining data quality. Technologies such as Linked Data and APIs enable semantic connections and real-time communication between systems. Additionally, automation can streamline integration, with AI-driven tools supporting data matching, cleaning, and transformation. The technology perspective was discussed in more depth in section 7.5.

By addressing these technical considerations, DBPs not only facilitate vertical and horizontal integration but also ensure that the job-sharing options outlined above are practically implementable.

### 7.6.4 A process modeling approach

The integration of the process element into workflows raises the question of how it dynamically interacts with other ISA elements. This section demonstrates how process modeling can be utilized to specify the process element effectively. A well-defined process model offers significant benefits, including:

- Standardization: Establishes consistent methods for using a DBP, critical for system administration and maintenance.
- User guidance: Facilitates intuitive interface design, allowing even non-expert users to navigate the system effectively.
- Function clarification: Distinguishes between automated system tasks and those requiring user intervention, ensuring clarity in operational workflows.
- Use case alignment: Addresses the information management needs of diverse actors by grounding processes in typical DBP use cases.
- Flexibility: Allows room for adaptation and customization, ensuring the DBP evolves alongside user requirements and technological advancements.

These advantages underscore the importance of process modeling in structuring dynamic workflows and integrating ISA elements.

To fully define these processes, it is crucial to specify how the system responds to user commands and manages interactions and workflows. This involves identifying and structuring the relationships between process components. A process modeling language is necessary to achieve this level of specification, and BPMN has been selected as a suitable framework for this purpose (section 2.3.4). While BPMN is traditionally used to model detailed business processes, its flexibility also makes it well-suited for modeling information management processes within a DBP. Not all BPMN capabilities are required for this application, but certain essential elements and their notations are particularly relevant.

At the core of BPMN models are activities, with the most basic form being a 'task.' Tasks represent functions as defined in the ISA and can be specified through activity markers, which indicate their execution behavior, and icons that identify task types (e.g. user tasks). For DBPs, most interactions occur between users and the system, making BPMN's more complex options for modeling user-to-user interactions less relevant. Data elements can be attached as artifacts to represent inputs, outputs, or data stores, helping to contextualize the functions and processes within the DBP.

ICT elements are not explicitly represented in BPMN but can be included indirectly by naming activities appropriately or adding annotations to specify their roles. Beyond the static elements of a DBP, additional process sub-elements are necessary to achieve a holistic process view. Events are used to indicate the start, intermediate interventions, or end of a process, while sequence flows, message flows, and associations connect the elements. Gateways function as logical operators to manage decision points within the workflow, ensuring the model captures the system's dynamic behavior accurately.

Table 7.9 provides an overview of how DBP elements are represented in BPMN:

Table 7.9: Representation of elements of a digital building passport in BPMN

| DBP element | Representation in BPMN |
|---|---|
| Functions | Activities, such as tasks, that can be specified through activity markers and icons for task types |
| Users | Specification of activities as user tasks; possibility to model user interactions through conversation, choreography, collaboration, or swimlane representations |
| Data | Simple data objects and more specified data objects, such as inputs, outputs, and data stores |
| ICT | Implicit consideration along with the definition of tasks; further specification through naming conventions and additional annotations possible |
| Process subelement: events | Explicit modeling of events that function as start, intermediate, or end of activities |
| Process subelement: relationships | Different types of flows, such as sequence flows, message flows, and associations |
| Process subelement: rules, policies | Gateways function as logical operators for connecting objects |

The respective notations for these BPMN elements can be found on the website of the Conferences on Business Process Management (Decker et al., 2010). By using BPMN, the clarity of the process element's role in integrating the ISA's static components into dynamic and functional workflows is enhanced. Camunda (2025) was used as a free BPMN modeling tool.

## 7.6.5 Holistic model view

This section aims to provide a conceptual understanding of how a DBP operates by presenting a process model that illustrates its key workflows. The process model serves as a framework for visualizing the integration of ISA elements into dynamic, user-driven interactions. By structuring the model at an abstract level, it highlights the core stages and relationships necessary for a DBP to function effectively, while avoiding excessive complexity.

The proposed model is divided into two primary stages (Figure 7.8). The first stage focuses on the initialization of the DBP, including user authentication and system updates to ensure readiness. The second stage centers on the execution of built-up functions, emphasizing user interaction and decision-making. Together, these stages provide a comprehensive yet simplified representation of how a DBP facilitates its various functions and processes.

The process begins when a user initiates the DBP software, which can also be interpreted as starting a session. Theoretically, multiple processes can run simultaneously, as DBPs are designed to be utilized by multiple actors. Starting the process model with user entry provides a clear framework for tracking a user's role throughout the process and linking it to tasks performed by the system. Other configurations are possible, such as running a DBP as a background application, but these are not the focus of this model.

When the DBP software is launched, two activities are triggered:

1. User login: The system prompts the user to log in. Authentication is carried out using predefined access policies and, potentially, specialized service providers (section X). If login fails, the user is given another opportunity to authenticate. Once successful, the user can proceed to interact with the system.
2. System updates: The DBP software checks for updates to ensure the tool operates at its optimal capacity. This includes reviewing the DBP's current state, such as existing elements and data, as well as updates from the service provider and the latest shared data from connected BISs. Automatic updates are implemented where possible, while updates requiring user intervention prompt a system-generated request. This functionality can also be used to notify building owners of significant real estate management tasks. Regardless of the specific updates, users are informed of any changes relevant to their role, adhering to service-level agreements and access policies.

The second stage of the process model begins when users decide which DBP function to apply. To facilitate this, a user-friendly interface should present various options. The interface can be personalized based on user access rights and preferences, informed either by user input or an analysis of previous interactions. Users navigate through the application to select a function. Upon selecting a desired function, they send an access request to the system by interacting with the appropriate interface element.

The system then evaluates the user's authorization for the requested action. This evaluation is governed by the access policy, with the authorization process potentially outsourced to an external service provider. In some cases, the user interface may be restricted to display only actions or items the user is authorized to perform, based on their role.

If the user's request is approved, the selected DBP function is executed through an interaction between user tasks and system tasks. This may include data interaction, generating insights, or administrative actions by the system to ensure the quality of the process. The distribution of tasks and user involvement varies depending on the specific function. The functions defined in the function element (section 7.2.2) require additional specification through distinct subprocesses. These subprocesses are excluded from the holistic model view to maintain simplicity and avoid excessive detail.

Finally, the process concludes when users decide whether to remain logged into the system and continue applying additional functions or log out, marking the end of the session.

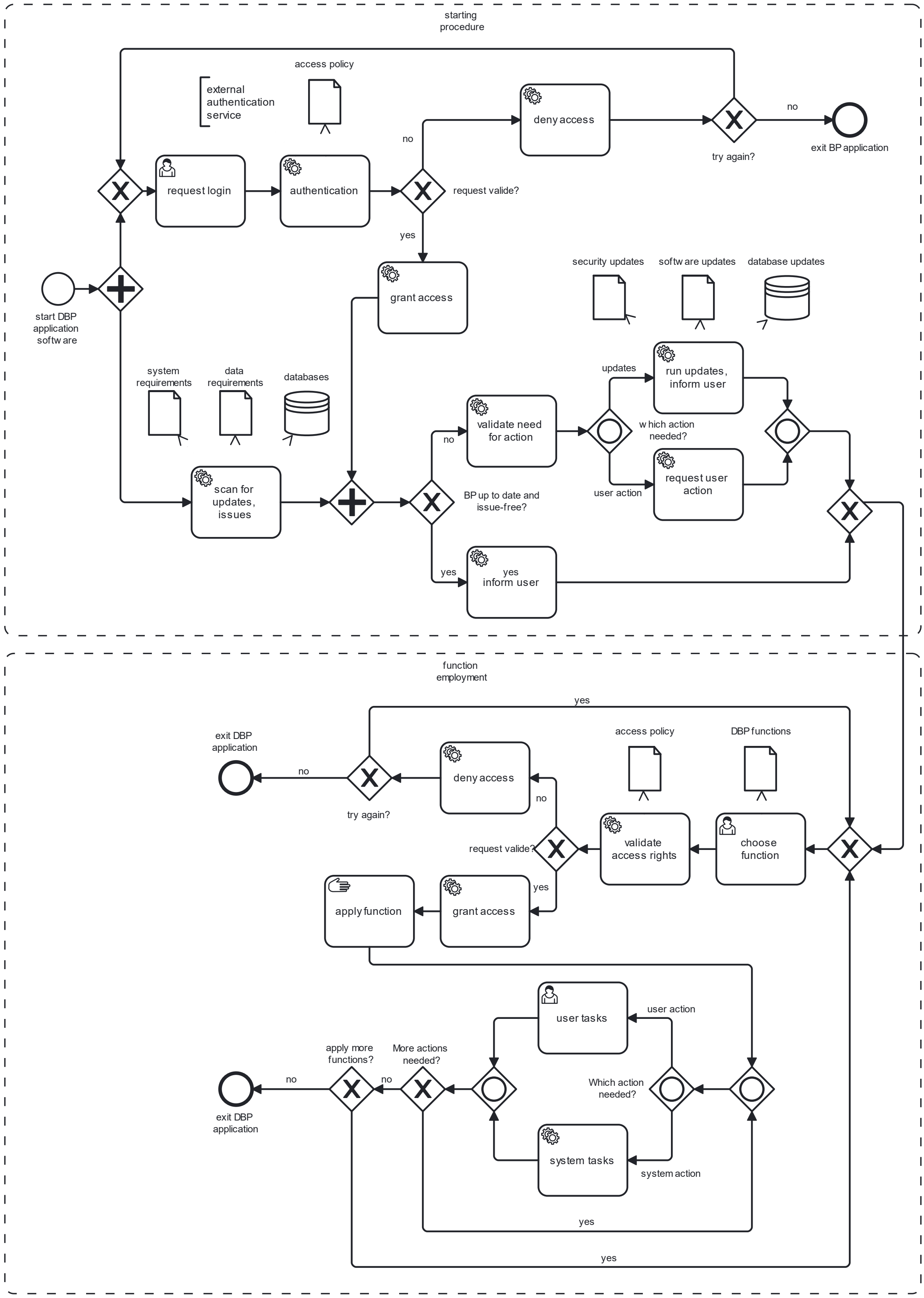



Figure 7.8: BPMN model for basic interaction with a digital building passport

### 7.6.6 Example process: data entry

To clarify how process modeling enhances the understanding of DBP functionality, an example process is presented for manually inserting data into a DBP. This process aligns with stage two of the holistic model view (section 7.6.5), where users interact with the system to execute specific functions. The example begins after a user selects a data-related function, allowing them to navigate through the data model to explore available data categories and elements based on their access rights and interests (Figure 7.9).

When users indicate their intention to insert data, the system first validates whether they are authorized to perform this action. If authorization is granted, the user is presented with various options for data insertion. These options depend on the type of building-related data and the functionalities supported by the system. Detailed implementation choices and associated business models are outside the scope of this process model view.

Given the heterogeneity of building-related data, the process model accommodates several methods for data insertion, including:

- Manual Entry: Direct insertion of individual data points by the user.
- Uploading Structured Data: Submission of data in interoperable formats, such as standardized files.
- Uploading Unstructured Data: Uploading non-machine-readable documents, such as PDFs.

If data are available as linked data, the DBP user does not need to insert the building-related data manually but instead utilizes a separate function to establish linkages. In any case, the DBP software processes the inserted data and validates its quality based on predefined data quality requirements. These requirements must be defined with precision to ensure a sufficient level of data quality while preserving the usability and efficiency of the system for the user. The data specification, namely the data ontology and dictionary, defines the semantics of the data, and newly inserted data must comply with these specifications. This ensures consistency and interoperability across the system while maintaining high data quality standards.

The outcomes of data quality validation may vary:

- Acceptance: Data meeting all quality requirements are immediately saved and applied by the system.
- Correction request: If issues are detected that can be resolved by the user, the system prompts the user to make the necessary corrections.
- Rejection: In cases of severe quality deficiencies, the data are rejected, and no changes are applied.
- Data transformation: Where applicable, the system employs data transformation techniques to align data with the required format. This may involve AI-driven algorithms, such as NLP, for extracting and structuring data from machine-readable documents or data cleansing techniques.

After processing and validation, the user can continue browsing the data model to insert additional data or exit the process, marking its completion.

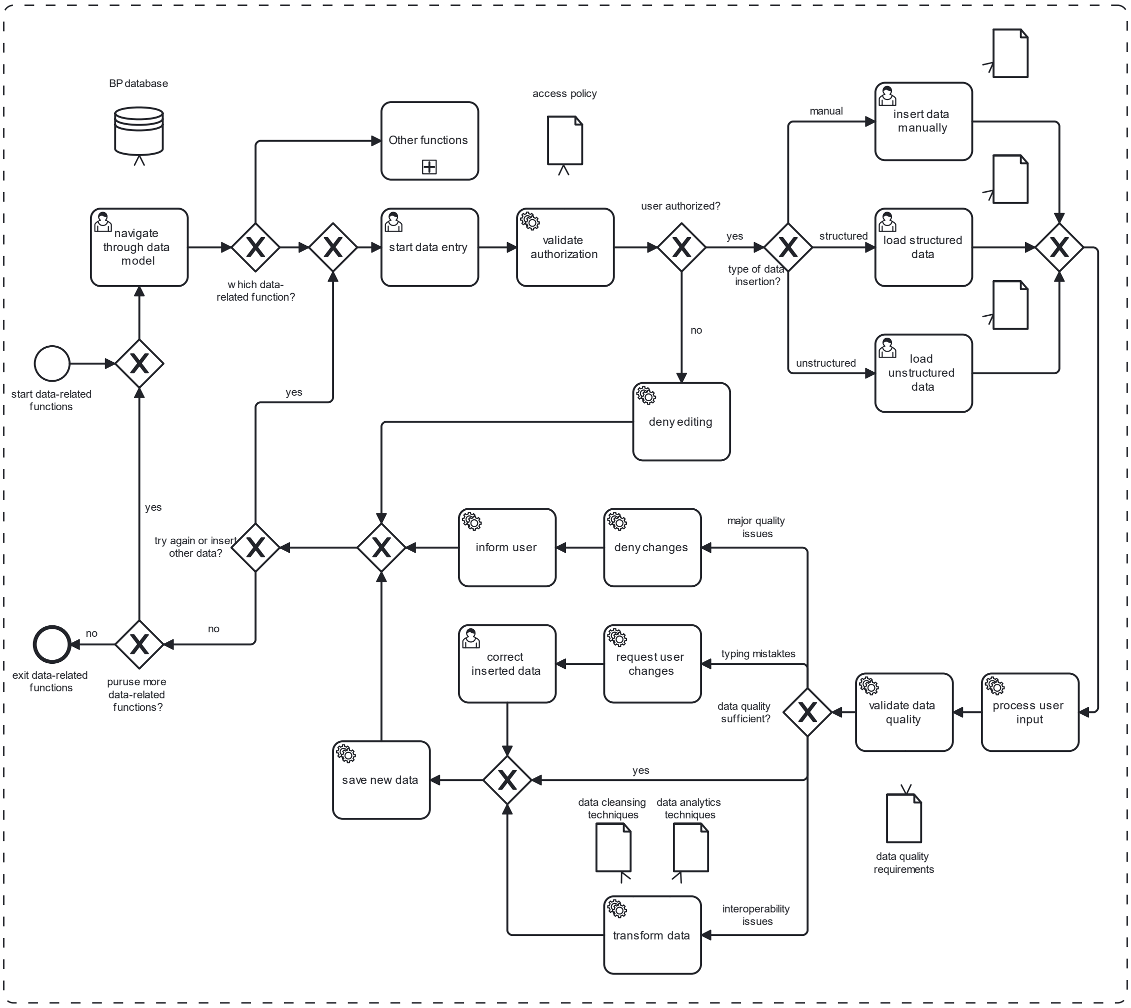



Figure 7.9: BPMN model for a data entry process in a DBP

## 7.6.7 Process model limitations

The proposed process model offers a conceptual framework for understanding how a DBP operates, focusing on the interaction of its system elements. This high-level approach provides clarity and supports the standardization of workflows, but it comes with inherent limitations. The model represents only a simplified view, covering selected functions to illustrate the dynamic relationships within the system. It does not encompass the full complexity of practical implementation, where workflows are more intricate and domain-specific.

The scope of the model is restricted to a subset of DBP functions, leaving out detailed subprocesses and edge cases. While this abstraction is useful for initial system design and communication among stakeholders, it may oversimplify the challenges of real-world applications, such as integrating heterogeneous data sources or aligning workflows with diverse user requirements. Furthermore, the validity of the process model depends on predefined assumptions, including user behavior, data quality standards, and system capabilities, which may not fully align with practical realities.

Despite these limitations, the process model serves as a valuable foundation for iterative development. It enables the refinement and fine-tuning of workflows as the DBP evolves, ensuring the system remains adaptable and relevant. To maintain its effectiveness, the model must grow alongside the functionality of the DBP, incorporating new use cases and technological advancements. This adaptability highlights the model's utility as a dynamic tool for guiding the ongoing development and optimization of the DBP.

# 8 Implementation and feasibility

*Based on the proposal of a conceptual framework in chapter 7, its practical feasibility and implementation will be discussed in the following. This includes references to former contents in this thesis, new proposals, and the aggregation of recommendations. The aim is to validate the ISA framework and detect aspects that need further elaboration to improve practical feasibility. In addition, the relevance of intermediate results, such as the taxonomy for building-related data needs (section B.7) or the requirement profile for DBPs (chapter 5), will be highlighted.*

*To do this, this chapter follows the following logic: First, a best-case scenario is envisioned how DBPs should be ideally implemented throughout the building life cycle and what role the ISA can play within each stage (section 8.1). This scenario sets the basis to specify potential benefits (section 8.2) and implementation barriers and challenges (section 8.3). Methodologically, this chapter draws on expert interviews that were conducted specifically for validation purposes (section B.1), as well as on prior analytical findings developed throughout the thesis. For two aspects that stick out, the economic perspective (section 8.4) and actor-specific perspective (section 8.5), implementation options are discussed including an example for business model development and a proposal for actor-specific solutions. Finally, recommendations are given for DBP implementation, use, and governance directed at the main addressees of this thesis (section 8.6).*

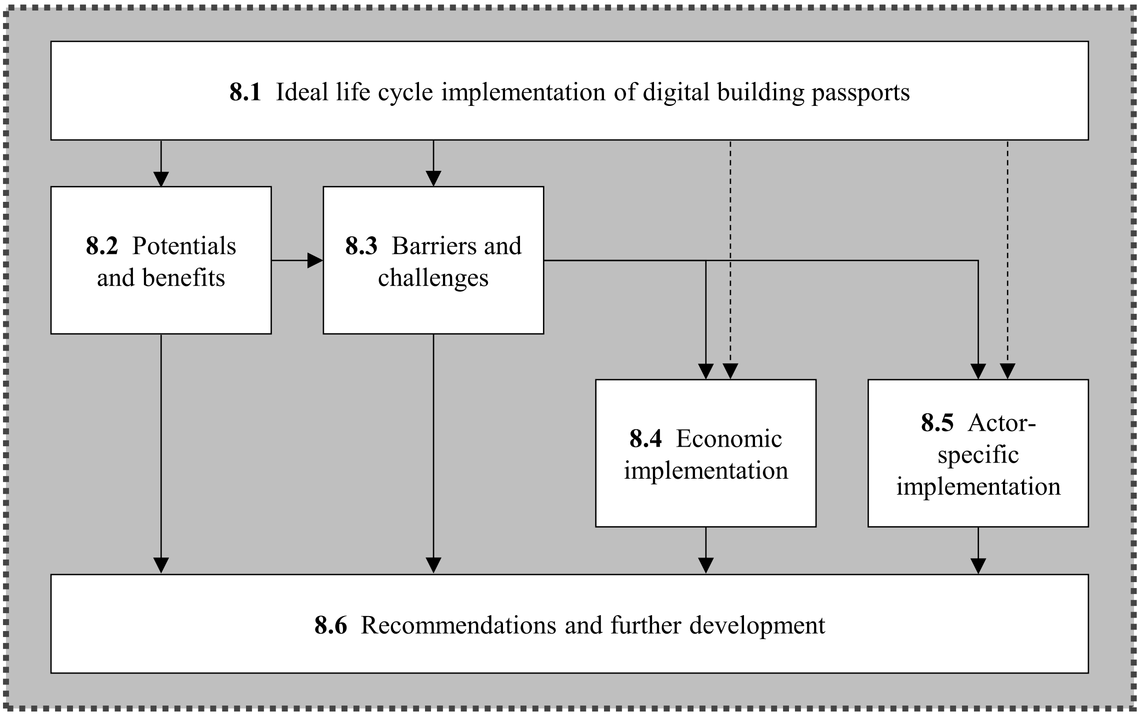



Figure 8.1: Structure of chapter 8

## 8.1 Ideal life cycle implementation of digital building passports

The following section outlines a best-case scenario for the implementation of DBPs as LC-BISs. It illustrates how DBPs can be embedded into information management across all life cycle stages, based on the proposed ISA and the broader results developed throughout this thesis.

### 8.1.1 Development

Functioning as a LC-BIS, a DBP usage is envisioned from the outset of a project development as part of a life cycle information management strategy. Requirements on such a tool are specified at an early stage. These requirements build on the requirement profile for LC-BISs, the ISA for DBPs, and the personal preferences of the actor. By specifying requirements early on, the foundation is laid for how data should be created, collected, stored, shared, and used throughout the life cycle as well as the goals that are pursued with it. The ISA in connection with the requirement profile help clarifying main concerns including:

- Which building-related data must be created and collected for the DBP?
- Which functions should the DBP fulfill to manage information throughout the life cycle?
- Which actors should be involved in the creation, use, and management of the DBP?
- Which data quality requirements are to be met?
- Which requirements are posed on the usability of the system?

Answering these questions can be carried out with predefined options, for example specified by actor-specific business models or by standardization. In the best case, requirements exceed minimum levels and cover the full spectrum of the requirement profile.

After defining the DBP strategy, a DBP is initialized. This includes the setup of all the essential elements of the DBP according to the ISA, so that it can function properly right from the start. This includes:

- Setting up the DBP platform and ensuring that core technologies, such as the cloud infrastructure, are working properly
- Setting up user profiles of actors which are already involved based on the DBP user model including the specification of user requirements
- Ensuring the security of the system and the data based on the security technologies and the preferences of the owner
- Establishing the connection to other BISs that are used throughout development and construction when necessary; this can include BIM models, construction project management tools, national building registers, or portfolio management systems, for example

After the initial setup phase, DBPs provide the structure for a systematic creation and collection of building-related data, which were specified as relevant. At the project development stage, this mainly covers master data according to the taxonomy of building-related data needs, such as building identifiers, actor information, location data, and first aspects of a planning log, which can later be kept as a planning record. In addition, crucial legal data are collected including property rights and legal liabilities as well as important contracts. To collect the required data points, requirements are posed to the actors that create these data, such as project developers, designers, or consultants. The information flows depend on the specific project organization structure, which can be contextually different for different building use types, countries, project sizes etc. Most likely, project developers will take in a key role in this process based on their coordinating task in project development.

**Best practice: DBP at the development stage**

- Specify requirements on the use of DBPs as part of a life cycle information management strategy
- Initialize the setup of a DBP and collect first data points that are created at this stage

### 8.1.2 Construction

A fluent transition from the development to the construction stage should be reflected in information management and in the use of DBPs. Since typically the amount of actors increases throughout construction, the functions of a DBP to collect building-related in a standardized way and share these data when needed become more relevant. Designers, project managers, surveyors, construction companies etc. are deeply engaged in creating and sharing building-related data at this stage. By functioning as the single source of truth for relevant data points, the DBP streamlines data collection. Thus, the DBP also facilitates a digital building permit process by making the necessary compliance data available to building authorities.

Throughout the construction process, the DBP provides guidance on the needs of building-related data at later life cycle stages. Important milestones are documented as well as crucial design decisions, concepts, and analyses. These data form the essential basis for the planning and construction record.

The most important aspect of DBPs at the construction stage concerns the end of construction, when the DBP provides a standardized framework for creating the as-built documentation of a building. Inventory data are created and collected based on the specifications of the DBP data structure. According to the taxonomy of building-related data needs this, among other things, includes geometries, material and mass data (potentially part of a dedicated material inventory), building component data, building services data, and functional building properties. The building geometry is integrated by linking or integrating a virtual building model to the DBP. Contractual agreements between owner, builder, and service providers, for example with a reference to HOAI documentation requirements as a basis, ensure that data are collected as required.

The inherent quality control functions contribute in connection with contractual agreements to better data quality. Based on its diagnostic data analytics function, the DBP automatically informs the user on missing data or potential data quality issues. The overall data quality is assessed by the system and a risk-return ratio assessment for information management in the life cycle is provided. Proposals are made to the responsible actor how data quality can be improved.

The standardized as-built documentation is used for important tasks, such as sustainability assessments or marketing. The results of sustainability assessments at this stage are integrated into the DBP according to the taxonomy of building-related data needs with contextual information integrated in a sustainability assessment log.

**Best practice: DBP at the construction stage**

- Keep a planning and construction log
- Make use of DBPs as a data sharing tool, e.g. for digital permit processes
- Create an as-built documentation at the end of construction based on the data structure of the DBP

### 8.1.3 Handover and transition

Since the transition from construction to use stage is potentially the most critical point for life cycle information management the DBP takes in a very crucial role here. As part of the handover process, a DBP facilitates the handover of building-related data

Apart from that, the transition phase includes the optimal setup of the DBP for the use stage. Connections to other relevant BISs, such as BAMSs, facility management systems, or digital twins need to be established when not already done at an earlier stage. If new actors, such as tenants, property managers, or facility service providers, enter into the life cycle, user profiles are created for these actors. This can include contractors in their role as dedicated stewards for managing DBPs for building owners. The setup of DBPs includes the activation of functions of the DBP according to the preferences of users. An owner activates data analytics functions which enable automated status reports on building performance, alerts regarding potential anomalies, and prescriptive analytics for building management. In addition, personal reminders are established for maintenance activities.

New data are added to the DBP at this stage to enable a seamless track of the building history. The construction record is completed and transferred into an immutable record, for example through data formats such as PDF/A or by making use of blockchain technology. At the same time, a real estate management log is initialized which contains relevant management decisions and processes throughout the use stage.

**Best practice: DBP at handover and transition**

- Use a DBP to handover building-related data systematically to the owner
- Prepare information management at the use stage by creating user profiles for relevant actors and linking DBPs to other important BIS

### 8.1.4 Use

Throughout the use stage, the DBP functions as a data repository representing the single source of truth for the integrated data. It provides a structured classification that assists the collection of building-related data. It provides regular status reports to the responsible user (owner, steward) on potential risks due to data quality issues or due to risks directly connected to the building. Based on the connection to BISs that are applied for technical monitoring, such as BAMSs, the DBP's databased is continuously enriched. Outdated data are archived as part of the maintenance and usage log, as specified by the taxonomy of building-related data needs.

The DBP meets crucial functions of information management throughout the use stage by enabling the systematic collection, storage, and sharing of data at different occasions. Actor information are updated when new actors enter into the building life cycle. A real estate management record ensures the documentation of substantial decisions and how facility, property, and portfolio management are organized. Critical changes to the building through maintenance are documented by updating the respective inventory data. These data are collected directly at the timing of data creation. The DBP functions ensure that data meet quality requirements through several ways. It offers ways to entry data for several formats. Structured datasets can be integrated conform to the DBP data model. Semi-structured or unstructured data are processed to ensure the machine-readability of these data, mostly applying to scanned documents. The combination of OCR with AI provides the capabilities to read relevant data points, such as energy consumptions, cost data, or actor information from documents.

The DBP predicts building performance over time based on the properties of building elements, such as the age or condition of structural building components, and based on energy and material flows. This facilitates the derivation of action plans for long-term maintenance and renovation. The proposals made to the responsible actor (e.g. building owner, real estate manager) take in the form of temporary action suggestions or complete renovation roadmaps. The DBP thus either fully integrates the functions of a building renovation passport as a dedicated microservice or is connected to a separated BIS through APIs or linked data. In any case, the DBP carries data that are relevant for renovation planning and decisions. These data are shared with actors that take part in the renovation process. Data owners, specifically building owners, trust the data sharing process since they can specify who can access or use data points. For major renovations, master data are updated including actor information, important dates, and an (as-built) construction record.

The DBP assists several other important tasks throughout the use stage by providing essential data points in a systematic way and/or by making use of these data through data analytics functions. This includes:

- Transactions: The DBP offers structured data for marketing, property valuations, and risk assessments. It can contain functions to generate real estate brochures, EPCs, valuation estimates or risk profiles in an automated way. For due diligences, it provides a structured overview on the available information and for necessary data collections.
- Renting: The DBP manages data that are essential for renting and tenant management. It facilitates data sharing between landlord and tenant. A landlord can manage tenant data,

cost and revenue streams, contracts, and compliance documents as part of a DBP. Based on data on the energy performance, a DBP can facilitate the generation of EPCs or at least provide essential data for this purpose.

- Portfolio management: DBPs function as the essential data source for real estate managers. Especially portfolio managers and asset managers profit from the consistent data base, when all buildings within their building stock have a DBP. Portfolio management software can link necessary data points from a DBP.
- National building registration: DBPs offer standardized and digital access to governments and public authorities to building data. Building registers and DBPs can mutually link to relevant data in the other instrument. For DBPs, this can refer to national building identifiers, for example, and for building registers all kinds of master and legal data that are necessary to manage the national building stock.

**Best practice: DBP at the use stage**

- ➢ Keep a continuous record of the building by documenting relevant changes
- ➢ Make use of building-related data from the DBP at various occasions, such as maintenance, renovations, transactions, renting, portfolio management, or national building registration

### 8.1.5 End-of-life

The systematic management of building-related data with a DBP becomes reasonably valuable at the end-of-life stage of a building, especially already at demolition/deconstruction planning. The DBP provides relevant inventory data on building elements, building materials, and potential hazards. Manufacturer information on building elements provide guidance on how certain materials should be treated for disposal or recycling. Mass and material data also help to evaluate potential environmental impacts of deconstruction.

Data analytics functions help analyzing the building's condition and provide decision-makers with proposals on what to look out for in a deconstruction. This includes hazardous materials as well as potential threats, for example through structural instabilities. By documenting the deconstruction process in a (de-)construction record, a building log is completed for the entire lifespan of a building. This building log can serve national or personal archives as a contribution to preserving cultural heritage. It also helps governments to track the performance of the national building stock over time.

**Best practice: DBP at the end-of-life stage**

- ➢ Make use of building-related data from a DBP to plan deconstruction and disposal
- ➢ Integrate the continuous and immutable building record to national archives

### 8.1.6 Handling existing buildings

The vast majority of buildings are existing buildings for which the best-practice implementation from the outset of the life cycle is not feasible. Thus, solutions are needed for a successful and efficient implementation of DBPs for these buildings too. To reduce administrative effort, synergy effects should be used that result from implementing a DBP at strategic points in the life cycle. Rather than treating DBP adoption as a standalone initiative, aligning it with occasions where building-related data are already being collected or consolidated can significantly reduce resource demands and enhance the quality of the resulting information. Optimal occasions include:

- Major maintenance or refurbishment projects, where significant building-related data are typically updated or generated.
- Transactions, property valuations and due diligences, which require comprehensive assessments of the building's current condition, legal status, and performance metrics.
- Sustainability certifications or assessments, where detailed performance data are collected and created.

The tasks that are connected with these occasions often go along with substantial building-related data needs. Not all of these data have to be collected through cost-intensive primary data collection directly at the building. Secondary data sources, such as as-built design documents, building permits, room books, virtual building models, facility management systems, building registers, and other BISs, should be prioritized. The data collected from these sources should be validated regarding its compliance with data quality requirements. Data processing through AI-enhanced OCR techniques helps to digitize these documents and make them machine-readable

Throughout the process, several elements of the ISA and other proposals for DBPs can be of use:

- The requirement profile helps actors to specify their requirements.
- The taxonomy of building-related data needs provides a structured framework for data collection and storage.
- The DBP assists users in managing data quality throughout the data life cycle process and by specifying data quality requirements for data points.
- The DBP provides the functionality to leverage the potential of secondary information sources by ensuring the machine-readability and digitization of documents and by reading data from documents through OCR and AI processing.

DBP implementation for existing buildings does not have to be bound to occasions at the building level. At the corporate level, DBP implementation can be embedded within broader transformation initiatives. Examples include:

- Digitization projects aimed at enhancing operational efficiency and transparency.
- Data quality improvement programs, addressing gaps or inconsistencies in existing building-related information.
- Cultural and organizational change initiatives, where DBP adoption is positioned as part of a forward-looking strategy to align with market trends and regulatory requirements.

By aligning DBP implementation with corporate-level goals, organizations can ensure that the process is both scalable and aligned with their long-term strategic vision.

Building and corporate level strategies are not mutually exclusive but can complement one another. For example, a corporate strategy might identify portfolio segments for initial DBP rollout, while individual buildings within those segments are prioritized based on planned maintenance schedules. This integrated approach, visualized in figure X, ensures that DBPs deliver value at multiple levels, fostering their broader adoption across the real estate industry.

### 8.1.7 Summary life cycle implementation

Figure 8.2 visualizes the ideal implementation of a DBP across all stages of a building's life cycle. Used as a LC-BIS, the DBP is initialized during development as part of a comprehensive information management strategy. Its implementation is guided by the proposed ISA, which defines the structure for managing data, processes, and user interaction consistently throughout the life cycle. The DBP enables systematic creation, collection, and exchange of building-related data, supports documentation and compliance processes during construction, and ensures continuity of information at handover and during use. In renovation and end-of-life planning, it provides access to key data such as inventory and condition information. For existing buildings, DBPs are introduced at strategically relevant moments, with the ISA supporting scalable and context-sensitive integration into existing processes and systems.

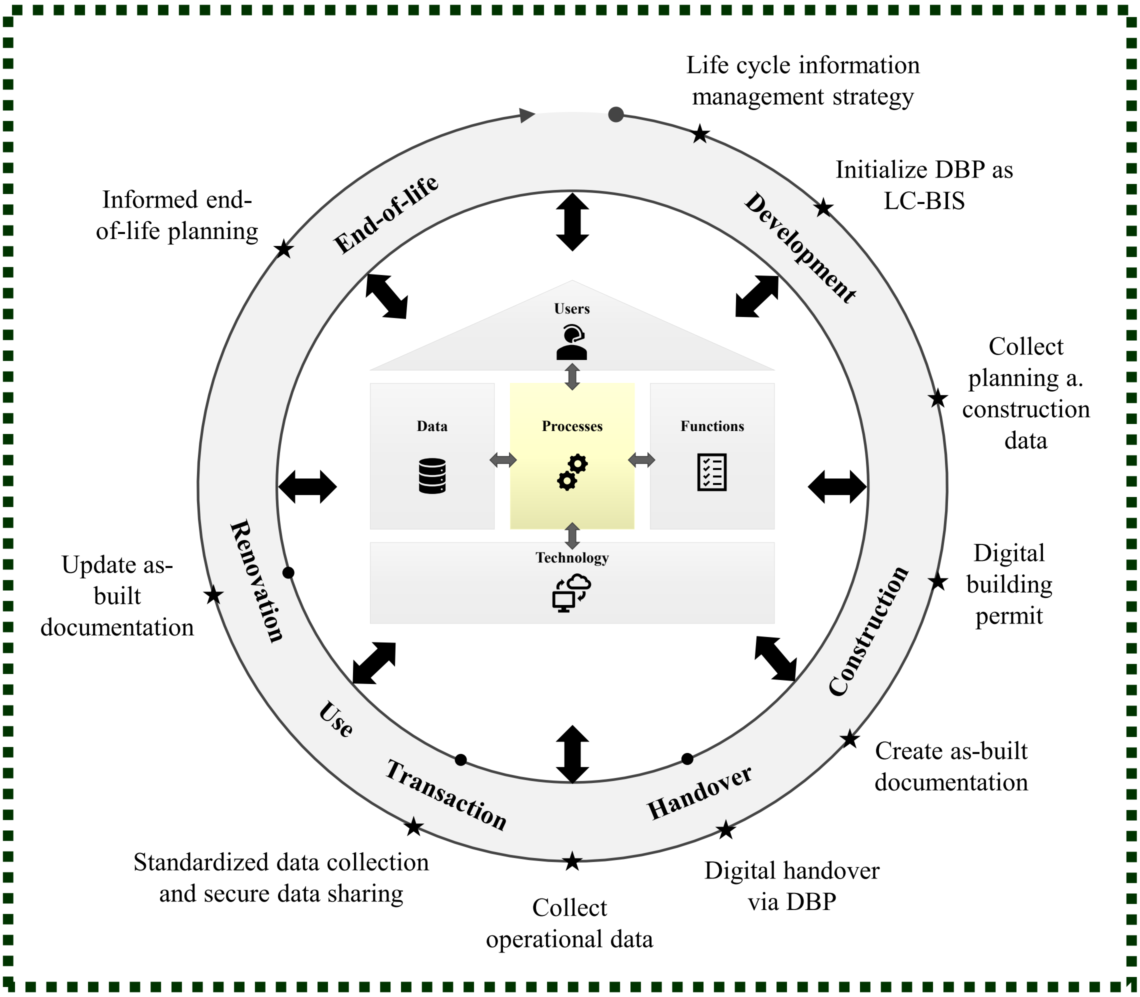



Figure 8.2: Milestones in implementing the digital building passport framework throughout the life cycle

# 8.2 Potentials and benefits

The best-practice implementation of DBPs, as outlined in section 8.1, offers substantial potential to fulfill their intended functionality as LC-BISs. These potentials span across several levels: they strengthen information management throughout the building life cycle (section 8.2.1) and, as a result, improve real estate management more broadly (section 8.2.2).

## 8.2.1 Benefits for information management

DBPs can provide effective information management solutions in their role as LC-BISs, as outlined in section 5.1.1. Several characteristics of the DBP framework proposed in this thesis stand out as key enablers of improved information management:

- Standardization: When implemented according to a common understanding of functionality, as defined in the ISA, DBPs can streamline essential processes such as the collection, processing, storage, sharing, and use of building-related data.

- Digitalization: DBPs support the ongoing digital transformation of the real estate industry by digitizing building-related documents and datasets. This creates the technical basis for applying modern ICT solutions.
- Simplification: As a single source of truth for relevant building-related information, DBPs can significantly simplify how data are managed by various actors.
- Control: Through decentralized data ownership, DBPs give actors full control over their data, which can help to foster trust and enable transparent governance.
- Alignment with operational needs: The DBP concept proposed in this thesis is grounded in the concrete information management requirements of relevant life cycle tasks. The focus lies in the structured identification and handling of data needs.
- Actor integration: DBPs can overcome existing data silos by integrating key actors in real estate management. They function at the level of individuals, across actor constellations, and potentially on an industry-wide scale.
- Data (quality) focus: DBPs place a dedicated emphasis on data as the core asset of information management. Data quality is addressed comprehensively, based on the requirement profile.

These characteristics contribute to improvements across two main dimensions: data quality and process quality (Figure 8.3). Enhancements in data quality extend across a wide range of dimensions, particularly those identified as strict requirements in the requirement profile for LC-BISs. The availability of accurate and reliable data is also a prerequisite for meaningful use of analytics functions. Process quality improvements relate to key functions such as guided data collection, quality control, and secure data sharing. By acting as a trusted source for building-related data, the DBP can address frequent information management issues, especially those linked to information asymmetries and fragmented responsibilities.

A central aspect connecting improvements in data and process quality is findability. Expert consultations suggest that difficulties in locating relevant data often present a more significant issue than the data's availability itself.

The benefits in information management are especially evident during specific tasks or occasions in the building life cycle. For instance, guided data collection is particularly useful in building surveys and sustainability assessments, while efficient data sharing is critical during handovers. The availability of building-related data that would otherwise have to be collected from scratch adds value across many data-intensive tasks, such as property valuations or due diligences.

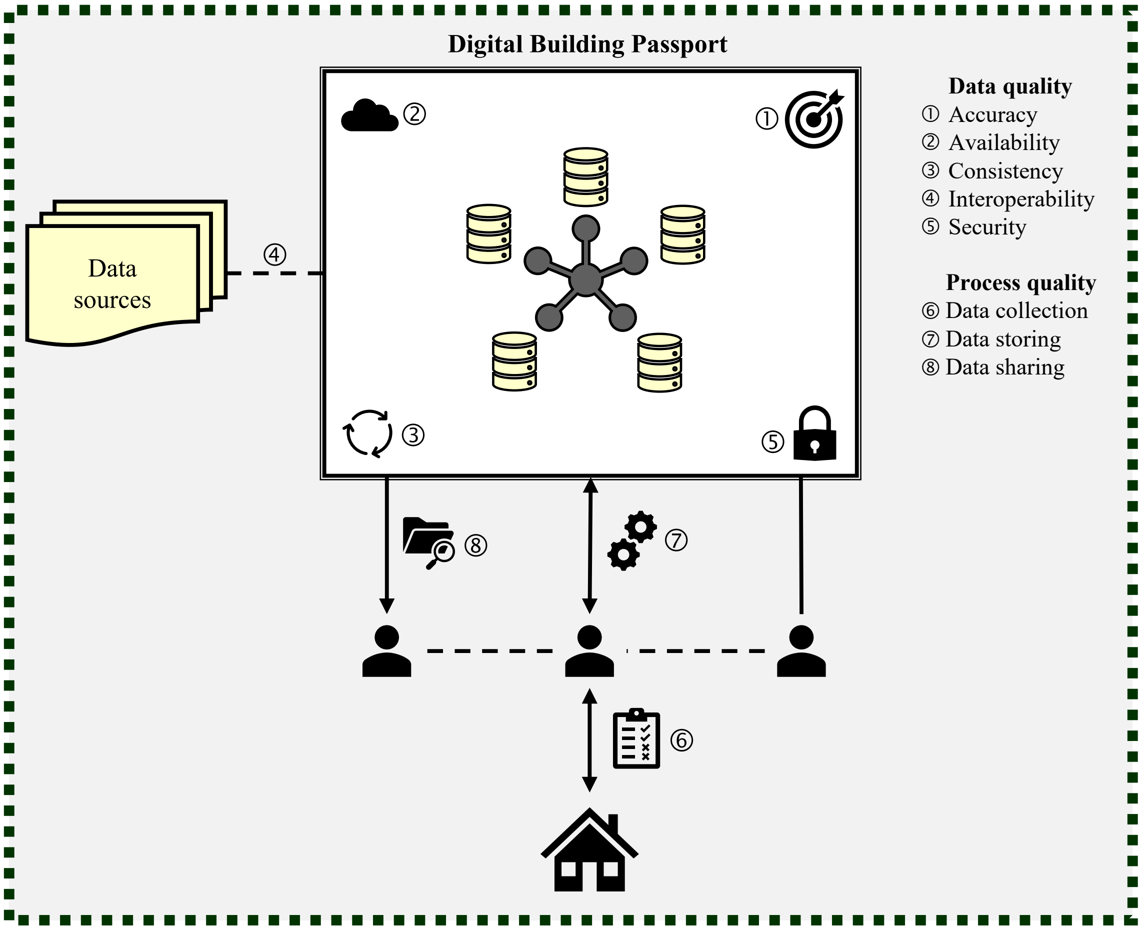



Figure 8.3: Overview on data and process qualities in a digital building passport

## 8.2.2 Benefits for real estate management

Information management is integral to numerous tasks across the building life cycle. Improvements in this domain, as enabled by DBPs, can have a direct and measurable impact on real estate management. Key benefits include:

- Operational efficiency: As defined in the requirement profile, DBPs must be both effective and efficient to ensure practical relevance. When implemented accordingly, they help users quickly locate relevant building-related data and streamline workflows within real estate companies.
- Strategic decision-making: A reliable information base enhances the quality of long-term decisions in areas such as asset strategies, portfolio management, and refurbishment planning.
- Risk mitigation: Reliable access to critical data helps mitigate risks associated with uncertainty, such as poor decision-making, loss of property value, or unexpected cost developments. A lack of up-to-date information, especially on building condition, can lead to inefficient or erroneous choices.
- Cost reduction potential: Continuous data collection throughout the building life cycle has been shown to be economically advantageous compared to sporadic data collection

(Mehlis, 2005, p. 204). Expert consultations confirm that DBPs could substantially reduce the costs of data collection and processing in tasks such as building surveys, due diligences, and sustainability assessments, especially when they provide high-quality data and structured guidance for collecting any missing information.

- Value enhancement potential: High-quality, accessible, and trustworthy data are increasingly viewed as a valuable asset. DBPs enhance the value of building-related data, which can positively affect marketability and perceived property value. Conversely, the absence of such information can result in value loss.
- Marketing and reputational advantages: Transparent, well-structured data management supports an owner's reputation and signals professionalism, especially in the context of sustainability and compliance.
- Improved collaboration: DBPs bring together multiple actors across the construction and real estate value chain. This extends beyond data sharing to new forms of collaborative workflows and potentially joint value creation.
- Innovation potential: DBPs provide a basis for innovation by making high-quality building-related data accessible for new services and digital applications. This includes automation, interactive data platforms, or AI-supported planning and analysis tools.

Despite these overarching benefits, practitioners may not always recognize the full value of improved information management. Expert interviews indicate that benefits such as improved data control are often intuitively linked to broader outcomes like operational efficiency, better decision-making, and lower risk. These insights underscore the existence of a chain of effects, where the core characteristics of DBPs first enhance information management and, through that, create value for real estate management more broadly (Figure 8.4).

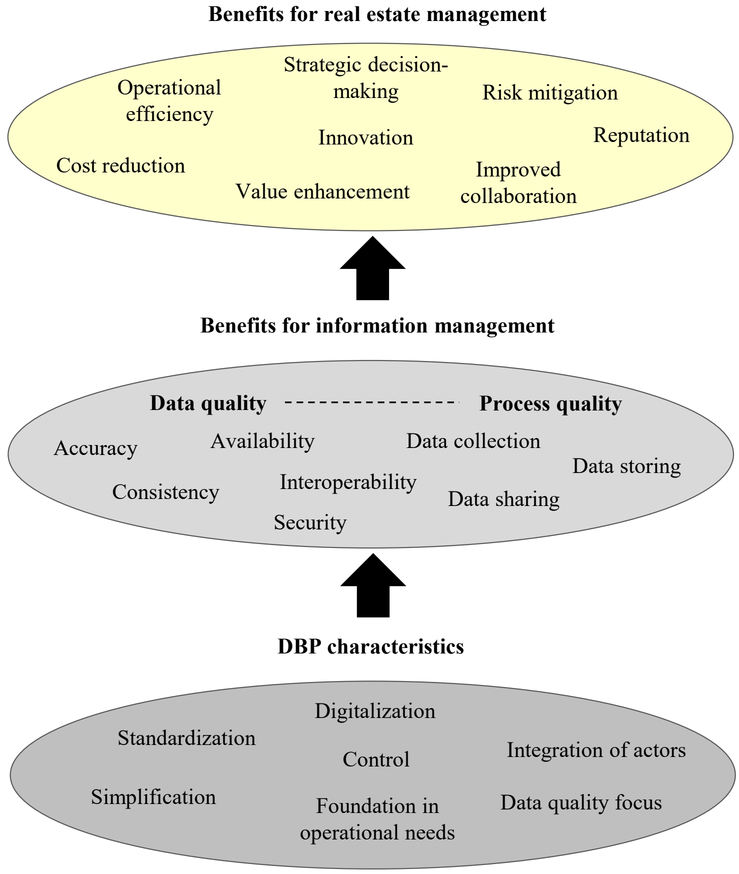



Figure 8.4: Chain of effects for benefits and potentials in digital building passports

A particularly common point raised in interviews was the potential for reducing the costs associated with data collection and processing. While uncertainty remains regarding the overall economic efficiency of DBPs, experts consistently identified specific situations where access to structured, high-quality data through a DBP would save time, reduce effort, and potentially eliminate the need for external service providers. For example, technical building surveys during due diligences can easily reach costs in the four- to five-digit euro range for larger buildings. If the DBP already contains validated data, these costs may be significantly reduced. However, interviewees also pointed out that ensuring data and process quality will always require some degree of effort.

In addition to cost savings, other benefits such as reduced decision-making risks, improved workflows, and enhanced stakeholder trust may be more difficult to quantify but are no less important. For example, DBPs support data-driven portfolio management and facilitate renovation planning, both of which can result in long-term efficiency gains and strategic advantages.

The specific tasks in which cost savings and efficiency gains are expected are summarized in Table 8.1. It outlines how DBPs can reduce effort in data collection, data sharing, and data analytics across selected real estate processes.

Table 8.1: Task-specific cost reduction potentials of digital building passports

| | Data collection | Data sharing | Data analytics |
|---|---|---|---|
| Digital building permits | ➔ | ↘ | ↘ |
| Construction documentation | ↗ | ↘ | ↘ |
| Commissioning and handover | ↗ | ↘ | ↘ |
| Use documentation | ↗ | ↘ | ↘ |
| Building surveys, inventories and due diligence | ↘ | ↘ | ↘ |
| Property valuations | ↘ | ↘ | ↘ |
| Risk analyses | ↘ | ↘ | ↘ |
| Public administration | ↘ | ↘ | ↘ |
| Sustainability assessments | ↘ | ↘ | ↘ |
| (Sustainability) reporting | ↘ | ↘ | ↘ |

The table shows that DBPs can streamline several processes by either eliminating the need for new data collection or by improving the accessibility and usability of existing data. Especially for recurring or documentation-intensive tasks, such as property valuations or reporting, the long-term reduction of manual effort offers significant economic advantages.

In a detailed economic evaluation, such as a business case or cost-benefit analysis, the potential benefits outlined above must be weighed against the specific costs associated with implementation. These costs can include licensing fees, system setup and administration, investments in ICT infrastructure, and user training. The timing of DBP adoption also influences the overall cost-efficiency. When introduced during modernization projects or aligned with data-intensive tasks, implementation costs may be significantly reduced by drawing on data already being collected (section 8.1.6). Furthermore, portfolio-wide implementation can lead to scaling effects, which reduce the average cost per building and further strengthen the economic case for DBPs.

## 8.3 Barriers and challenges

While the previous section outlined the potential benefits of DBPs, their implementation remains confronted with various barriers. These challenges reflect the complexity of DBPs as LC-BISs and their interaction with technical, organizational, and regulatory conditions. The following subsections distinguish between barriers that can be addressed through the proposals developed in this thesis (8.3.1) and those that persist beyond its current scope (8.3.2).

## 8.3.1 Addressed barriers

In the past, several severe barriers have hindered the successful implementation of building passports. To provide a structured overview of these challenges, evidence from existing literature is provided in section G.1. This compilation identifies key barriers repeatedly discussed across academic studies and policy papers. The barriers can be grouped into five overarching dimensions:

- Political and legal: including regulatory fragmentation, unclear responsibilities, and lack of public-sector prioritization.
- Economic: involving uncertain value propositions, high implementation costs, and insufficient business models.
- Technical: referring to challenges such as limited interoperability, poor legacy data integration, and unclear data standards.
- Actor-based: including low motivation, limited digital skills, and operational disconnects.
- Tool-related (functional): relating to usability, unclear scope, and the absence of robust governance mechanisms.

The results and proposals developed within this thesis contribute to overcoming a number of these barriers. Most notably, the requirement profile and the ISA serve as key instruments for clarifying system functionality, data requirements, and user interaction. Together, they address issues of inconsistent scope and purpose, a common problem in past initiatives. The clear distinction between DBPs and other types of BISs also helps position DBPs more precisely within the broader digital ecosystem.

Barriers related to data quality are tackled through the definition of minimum and extended data quality requirements in section 5.5, and through the system-side functions that support their implementation. The ISA integrates data quality checks and mechanisms for guided data entry, contributing to higher reliability and consistency of the collected information. While interviewees acknowledged the potential of these measures, some remained skeptical about whether organizational routines and corporate cultures would sufficiently prioritize data maintenance. Nonetheless, many agreed that a well-designed DBP could actively support improvements in these areas by making information management more transparent and structured.

From a technical perspective, most interviewees agreed that the necessary technologies for DBP implementation already exist. The thesis proposes a modular system architecture that facilitates the integration of different data sources and interaction with existing systems via APIs or linked data approaches. However, it was also emphasized that technical solutions must be adapted to the specific digital maturity levels of different actor groups to be practically effective.

In terms of actor-related barriers, the proposed user model and decentralized data ownership strategy directly address the challenge of limited user engagement and unclear responsibilities. By enabling actors to retain control over their data while delegating management tasks to designated stewards, DBPs can align better with operational realities. Furthermore, the focus on modularity and user-specific profiles enhances usability and lowers the entry threshold, particularly for smaller or less technically advanced actors.

Finally, economic concerns are acknowledged throughout the thesis. While cost-related barriers cannot be fully removed through technical design alone, the strategy of aligning DBP implementation with existing life cycle events, such as modernization projects or due diligences, offers a pragmatic way to reduce setup costs. Additionally, the benefits outlined in section 8.2 help clarify the potential long-term value of DBPs, particularly when implemented at scale.

Table 8.2 provides selected examples of how specific barriers are addressed in the thesis.

Table 8.2: Selected barriers to digital building passport implementation and how they are addressed in this thesis

| Barrier Type | Barrier Description | Addressed through... |
|---|---|---|
| Tool functionality | Unclear scope and purpose | Requirement profile; conceptual differentiation from other BISs |
| | Lack of user-friendliness | ISA with role-based user model and modular interface design |
| | Data governance issues | Decentralized ownership model and access management in ISA |
| Data quality | Unclear requirements for data quality | Requirement profile; quality management functionalities in ISA |
| | Inconsistencies across data sources | Taxonomy of data needs; lifecycle-oriented structuring |
| Technical | Interoperability challenges | Modular system architecture; support for APIs and linked data approaches |
| | Integration of legacy data | Secondary data strategy; AI-supported digitization (e.g., OCR + AI) |
| Actor-based | Lack of motivation and unclear benefits | Improved user control; illustrative use cases and link to strategic decision-making |
| | Skills and resource limitations | Simplified design and ability to assign stewardship roles |
| Economic | High setup costs and unclear funding | Cost-benefit discussion in section 8.2; timing alignment with data-intensive events |
| | Uncertain value proposition | Functional and strategic benefits mapped to use cases and actor tasks |

While not all barriers can be eliminated solely through conceptual or technical improvements, the proposals developed in this thesis provide a robust foundation for overcoming many of the persistent challenges identified in earlier research. The remaining barriers, which go beyond the technical and structural level, are discussed in the following section.

### 8.3.2 Persisting challenges

While a number of key barriers can be mitigated through the requirement profile, ISA, and implementation strategies proposed in this thesis, other challenges remain unresolved. These persisting barriers relate less to system design and more to questions of economic feasibility, organizational capacity, and actor-specific prerequisites for implementation.

A central open issue concerns the economic and financial dimension of implementation. Although DBPs offer cost reduction potentials across many life cycle tasks, there remains considerable uncertainty about who will develop, operate, and maintain DBP solutions in practice. Business models are still in niche markets, raising questions about who delivers DBP-related services, how they are financed, and what compensation models apply. In interviews, concerns were also raised about vendor lock-in effects, especially in contexts where proprietary systems or closed platforms dominate. Moreover, the future role of the public sector remains unclear. It is uncertain whether DBPs will be supported, endorsed, or even mandated as policy instruments, and to what extent this might influence their adoption across the market.

Another layer of complexity lies in the organizational and operational integration of DBPs. Their successful implementation requires not only technical infrastructure, but also adequate training, redefinition of roles, and often the creation of new workflows within organizations. Interviewees emphasized that even the most well-designed DBP is unlikely to unfold its potential if foundational workflows for data handling and documentation are not in place. This challenge is especially pronounced in organizations where information management is not yet institutionalized or lacks assigned responsibility.

In addition, actor-specific conditions present significant variation in readiness and capacity to adopt DBPs. Expert interviews highlighted the considerable differences between large, professionally managed real estate firms and smaller actors such as housing cooperatives or private owner-occupiers. These differences relate not only to financial resources but also to digital competencies, organizational structures, and levels of motivation. It remains an open question how different actor types can be addressed more specifically and how their respective needs can be translated into tailored support measures or phased implementation strategies. Interviewees also asked how actors should begin preparing for DBP adoption and what basic conditions must be met to ensure success. These concerns point to a broader requirement for transformation guidance that goes beyond the technical design of the system and engages with organizational change and capacity-building.

In summary, while the framework proposed in this thesis addresses several implementation barriers, some challenges remain. These include unclear business models, the role of the public sector, and varying prerequisites among actors. Two of these aspects will be addressed in more detail: section 8.4 explores options for economic implementation, and section 8.5 discusses actor-specific implementation considerations.

## 8.4 Economic implementation

Understanding the economic perspective of DBPs is essential for evaluating their feasibility and potential for adoption in the real estate industry. This section examines how DBPs can create economic value by exploring different development pathways and initiator models (section 8.4.1) and outlining viable business model strategies (section 8.4.2).

### 8.4.1 Development pathways and economic models

One major reason for the slow adoption of DBPs is the uncertainty surrounding their economic feasibility. There are no best-practice examples from prior implementations, and only limited academic or practical exploration of the economic aspects of DBPs exists. A key approach to clarifying their potential is the development of viable business models. However, there is no consensus in theory or practice regarding which actors should lead these models. Depending on the initiator type, multiple implementation options emerge:

- Private sector profit-oriented initiatives (i.e. a business): These initiatives may operate as standalone or integrated product/service offerings, typically involving one actor as the seller and another as the user. Various business relationships and models can be developed, with each business distinguished by the uniqueness of its business model.
- Non-profit-oriented private sector initiatives: These initiatives often have functionality similar to profit-oriented businesses but aim to address specific technical, environmental, or social challenges rather than generate profit. They range from large non-governmental organizations (NGOs) to groups providing open-source (software) solutions.
- Private developments for in-house use: Companies with substantial real estate portfolios increasingly recognize the value of tailored information management solutions. Customized in-house DBPs can address their unique needs, particularly for companies in the real estate industry or those with CREM departments.
- Public sector initiatives: Governments, with their substantial demand for building-related data, can play a key role in DBP development. They may either stimulate private-sector initiatives, leading to voluntary adoption, or mandate DBP usage through policy instruments.

These implementation pathways are not mutually exclusive and may coexist. As discussed in the literature on building passports and DBLs (section 6.2), examples of each approach already exist. Public initiatives, such as those launched in Germany and the UK, have so far failed to achieve widespread adoption. In contrast, recent years have seen an increase in private-sector activities, often driven by digitization efforts and sustainability goals.

There is no definitive answer as to which implementation path is most likely to succeed. The central question remains which option offers the greatest potential for widespread DBP adoption while meeting functional requirements. To support this evaluation, Table 8.3 summarizes the main advantages and disadvantages of each approach:

Table 8.3: Advantages and disadvantages of digital building passport development options by initiator type

| Initiator | Advantages | Disadvantages |
|---|---|---|
| Private sector profit-oriented initiatives | Access to resources for established companies;<br>High level of innovation;<br>Flexibility to adapt business models to trends;<br>Strong incentives for diffusion through financial gains;<br>Focus on customer needs through value propositions | Profit-driven decisions may overlook social and environmental goals;<br>Limited incentives for standardization, risking lock-in effects;<br>High costs for early adopters |
| Non-profit-oriented private sector initiatives | Long-term sustainability-oriented goals;<br>Generally more affordable for users due to non-profit nature | Limited resources compared to profit-driven businesses;<br>Risk of less efficient solutions with reduced functionality and customer focus |
| Private developments for in-house use | Enables highly customized solutions;<br>Often builds on existing real estate information management systems | Limited interoperability;<br>Solutions tailored to specific companies' needs |
| Public sector initiatives | Focus on societal and environmental well-being;<br>Opportunity for international alignment (e.g., EU initiatives);<br>Access to diverse resources;<br>Multiple roles in real estate incentivize holistic perspectives | Potential welfare loss due to market interventions;<br>Short-term focus driven by election cycles;<br>Bureaucratic inefficiencies and high costs |

While each option has distinct advantages and limitations, the pathway most likely to support DBP adoption will vary depending on market structure, regulatory environment, and timing. A plausible scenario, based on current trends, is as follows: the public sector continues to refine the DBP concept through research initiatives and develops a framework for industry application. Standardization bodies may then formalize this framework, defining key requirements and functions. Building on this, private-sector initiatives can create tailored DBP solutions that meet specific market needs.

The next section explores how such solutions can be structured through viable business models and strategic approaches.

## 8.4.2 Business model design

### 8.4.2.1 Strategic considerations

One major reason for the limited adoption of DBPs in the real estate industry is the lack of successful business models and practical examples. As outlined in section 8.3, several barriers have contributed to the failure of earlier initiatives. These include high initial costs, insufficient value recognition, and limited digital readiness. The inherent complexity of the real estate domain adds further challenges. The industry involves a wide range of actors with differing goals, from planning and construction to long-term use and management.

A DBP business strategy must respond to these diverse needs by identifying specific customer segments and tailoring the product accordingly. While many buildings share core characteristics, each one remains a complex and unique object with a long service life. A viable business strategy must clarify which building types and uses to target and how the DBP aligns with their specific demands. Additionally, the large number of existing information systems has led to confusion regarding terminology and functionality. A clear position within the BIS landscape which emphasizes the distinct role and value of the DBP, as shown in section 7.6.3, is therefore essential.

Common reasons for past business model failures include:

- Low willingness to pay due to the undervaluation of structured information management
- High upfront costs for data collection, quality assurance, and system integration
- Resistance to innovation and dominance of established software providers
- Absence of standardized DBP functionalities and data elements
- General startup risks such as unclear value propositions and limited market understanding

These cases show that there is no one-size-fits-all formula. Instead, a range of strategic options exists. Competitive models can demonstrate different development paths and may generate follow-up opportunities. These include integrated services, partnerships, or complementary offerings that increase market appeal and functional coverage.

Motivations behind DBP development can be economic, environmental, social, or personal. While financial performance is necessary to remain viable, motives such as improving sustainability and enabling better decision-making can strengthen the strategic foundation. Businesses aiming to enhance building information management may simultaneously support environmental goals, leading to solutions that serve both commercial and public interests.

### 8.4.2.2 Types of building passport business models

Business models for DBPs can be oriented around different stages of the DBP life cycle, particularly the development and use phases. While development requires significant investment in software design and infrastructure, the use phase offers the primary opportunity to deliver value through services, maintenance, and integration into existing processes. Unlike physical products, DBPs can scale efficiently once developed, provided they are supported by reliable infrastructure and services.

Several business model options exist and are outlined in section G.2. These include product-based sales, integrated product-service solutions, service-based models, contractor-based models, intermediary approaches, and peer-to-peer development. Each model defines different relationships between DBP developers, service providers, and users.

- Product-based models focus on selling a standardized DBP product to building owners or operators. These models allow developers to concentrate on software development and scalability but often lack support structures that many users require, particularly non-experts.
- Integrated product-service solutions provide a more comprehensive offering. Here, the developer or provider supports DBP use over time, assisting with data entry, compliance, system maintenance, and updates. This model increases trust and usability, especially among users with limited expertise, but may challenge scalability and require significant resources.
- Service-oriented models separate the DBP product from the services provided, allowing independent service providers to manage or supplement the system. This encourages specialization and flexibility but requires coordination and multiple contractual relationships.
- A more structured version of this model is the contracting approach, in which building owners outsource DBP management to specialized contractors under performance-based agreements. Contractors can assume the role of digital information managers, supporting data quality, regulatory reporting, and long-term data administration.
- Intermediary-based approaches rely on actors such as architects, facility managers, or housing associations to distribute DBPs as part of broader services. These intermediaries can create synergies and expand reach but may increase user costs and reduce transparency in the customer relationship.
- Peer-to-peer approaches involve real estate actors co-developing a DBP for shared use, such as through industry initiatives. These models enable strong alignment with sector-specific needs but are typically limited to actors with similar goals or capacities, which can restrict broader applicability.

A simple product-only model is unlikely to achieve widespread adoption in the real estate industry, particularly given the complexity of data and limited digital expertise among many users. More comprehensive or modular models that combine product and service components are better suited to accommodate diverse user needs, ensure data quality, and support long-term use.

#### 8.4.2.3 Value proposition

A clearly defined *value proposition* is essential for any DBP business model. It determines how the product or service addresses specific customer needs and creates benefits that justify its use and cost. For DBPs, this centers on improving the management of building-related information, particularly by reducing inefficiencies, ensuring data quality, and enabling better decision-making throughout the building life cycle.

Drawing on the logic of the value proposition canvas (section 2.3.5), DBPs can be framed through the lens of customer tasks, pain points, and desired gains:

- Tasks relate to the handling, use, and exchange of building data.
- Pains include fragmented documentation, low data usability, and time-consuming administrative processes.
- Gains reflect outcomes such as legal certainty, process efficiency, or better planning and sustainability performance.

Many of these aspects are explored in more detail in section 8.2 on potentials and benefits, which highlights how DBPs contribute to improved information management and, in turn, support broader real estate objectives. While that section emphasizes systemic improvements, the value proposition focuses more directly on how these benefits resonate with customer needs and expectations.

To make these benefits tangible, the following examples demonstrate how DBPs can address user challenges in practice:

- "Simplify your building information management with a single, secure repository for all data and documents, accessible anytime you need it."
- "Ensure transparency and traceability by storing comprehensive data throughout your building's lifecycle."
- "Streamline data transfer from design to operation with real-time input capabilities."
- "Make informed investment decisions with data-driven insights tailored to your property's unique characteristics."
- "Plan refurbishments with ease using automated tools that optimize cost, sustainability, and performance."
- "Take control of your building's data by deciding who can access and use it, empowering your decision-making process."

These examples illustrate how DBPs not only simplify technical tasks but also contribute to broader strategic goals, such as operational reliability and sustainability. A successful value proposition must align with the targeted use cases and customer segments while reflecting the broader advantages DBPs offer across the building life cycle.

#### 8.4.2.4 Customers

A successful DBP business model depends on clearly defined *customer segments*, effective delivery channels, and appropriate customer relationships. In the context of DBPs, customers can be found throughout the real estate value chain. Building owners, both private and institutional, are central customers as they typically hold and manage most of the relevant building data. However, other actors, such as property managers, architects, service providers, or consultants, may also be relevant depending on the use case.

Crucially, DBP business models must bridge the gap between data providers and data consumers. Building owners or project participants often provide data, while a wide range of actors, including regulators, investors, facility managers, or certification bodies, may need structured access to these data for specific purposes. DBPs can serve as a neutral and secure platform enabling this interaction, and a successful model must define how value is created for both sides. For example, a housing company may enter data into a DBP primarily for internal use, while also enabling external parties to retrieve verified information for ESG reporting or due diligence.

This intermediary role makes it essential to identify not only the primary customers who purchase or operate the DBP, but also the secondary users who benefit from access to the information it contains. Understanding this multi-sided dynamic is key for product design, service offerings, and pricing models.

A DBP business model may therefore target multiple customer groups through the same or differentiated offerings. While roles in the real estate industry provide a starting point for segmentation, further refinement is possible through firmographic, building-related, geographic, and behavioral criteria, as shown in Table 8.4.

Table 8.4: Customer segmentation criteria for digital building passport business models

| Category | Criterion | Explanation/Examples |
|---|---|---|
| Firmographic | Size of company | Based on revenues, employees, or market share. |
| | Size of building stock | Small, medium, or large portfolios of buildings. |
| Building-related | Building use type | Differentiation by building types (e.g., residential, commercial). |
| | Building age | Older buildings often present greater data challenges but also opportunities. |
| | Economic factors | Segmentation by property value or household income. |
| | Environmental factors | Segmentation based on $CO_2$ emissions, energy consumption, or environmental footprint. |
| Geographic | Location | Regional or national segmentation. |
| | Language | Language preferences for products/services. |
| Other factors | Demographic | Criteria like occupation or age. |
| | Technographic | Technical requirements or existing IT infrastructure. |
| | Psychographic | Customer interests, values, and priorities. |
| | Behavioral | Patterns of technology use and engagement. |

In early stages, it may be necessary to focus on a limited number of segmentation criteria due to resource constraints. Over time, more sophisticated targeting strategies can emerge.

*Distribution channels* for DBPs depend on the chosen business model. Industry networks, especially among housing providers, planners, and facility managers, offer important starting points. While digital marketing plays a role, direct channels such as professional associations, business events, or bundled offerings through existing service providers may be more effective in reaching target segments.

*Customer relationships* also vary depending on the business model and target group. For DBPs, common relationship models could include:

- Self-service, where customers independently use the DBP. This is less suited to complex building information systems without significant support structures.
- Automated service, where built-in features guide users through tasks and ensure consistency.
- Personal assistance, often provided through help desks or messaging portals.
- Dedicated personal assistance, such as assigning a specific contact person, particularly in bundled service models.
- Communities, which support user-to-user knowledge exchange and product improvement feedback.
- Co-creation, involving customers directly in improving DBP functionality or data offerings.

The choice of relationship model should align with the value proposition and the complexity of the services offered. For example, highly automated DBPs may benefit from community and co-creation strategies, while more customized solutions may require close personal support.

#### 8.4.2.5 Infrastructure

The infrastructure behind a DBP business model includes the *key activities*, *resources*, and *partnerships* needed to deliver its value proposition. For DBPs, this involves not only software development and operation but also the continuous support of users and the management of complex data flows throughout a building's life cycle.

Key activities vary depending on the chosen model. Product-oriented businesses focus on software design, prototyping, and scaling. Service-based models additionally require capacity for onboarding, user support, system maintenance, and compliance-related updates. In DBPs, ensuring system functionality over time is critical, especially when data must remain accurate and accessible across ownership changes and building stages.

Resources for DBP businesses are primarily intellectual and human. These include software architecture, data schemas, and regulatory know-how, as well as qualified personnel for development, customer service, and system maintenance. Financial and physical resources play a secondary role, especially for cloud-based service models.

Partnerships are essential for scaling and for fulfilling specialized tasks. Strategic alliances with service providers, IT partners, or real estate actors can help improve service delivery and extend market reach. Examples include:

- Authentication and authorization service providers for secure access management
- Cloud or data infrastructure partners to ensure scalability and reliability
- Consultants or contractors who take over DBP operation and data quality management on behalf of building owners

Outsourcing parts of the service, such as helpdesk support, infrastructure hosting, or data analytics, can reduce costs and enable DBP providers to focus on their core offering. However, it requires clear interfaces and quality controls to maintain system performance and user trust.

Specialization within the partner network becomes particularly important when DBPs are operated as part of broader real estate services. A facility manager offering DBP administration, for instance, may rely on integrated IT partners and external compliance experts. These constellations illustrate how DBP infrastructure must be modular and flexible, adapting to different actor roles and business models.

#### 8.4.2.6 Finances

The financial perspective of a DBP business model addresses how value is captured and sustained through appropriate *cost structures* and *revenue streams*. While DBPs are primarily software and service-oriented, financial planning must reflect the long-term nature of building use and the complexity of information needs.

The cost structure includes expenditures for development, maintenance, user support, and partnerships. Costs may be fixed, such as salaries or software hosting, or variable, such as those linked to service volume or onboarding new customers. For DBPs, human resource costs often dominate, especially during early-stage development and customer support. Where possible, automation and outsourcing can reduce operating costs, but this requires careful coordination with partners and quality assurance.

The revenue model must be aligned with the value proposition, customer segments, and product design. For DBPs, two main types of revenue streams are common:

- Transaction-based revenues, such as one-time sales or licensing fees, provide immediate income but offer limited potential for ongoing engagement or value capture.
- Recurring revenues, such as subscriptions, service contracts, or pay-per-use arrangements, ensure more stable income, support long-term relationships, and are generally better suited to the evolving data needs of buildings.

Pricing strategies must also consider the irregular nature of information demand in the real estate industry. For example, the need for complete and accurate data often arises during specific events, such as transactions, refurbishments, or regulatory reporting. This intermittent demand can make it challenging to define continuous value and requires tailored pricing and service models that reflect use cases rather than continuous usage.

To address this, DBP businesses can benefit from multi-actor revenue strategies. Instead of relying solely on building owners, they may also engage property managers, consultants, or public bodies that benefit from access to structured building data. This approach not only distributes costs across stakeholders but also increases acceptance and value recognition.

Capturing the monetary value of data remains a general challenge. The success of DBP business models will depend on how convincingly they communicate the benefits of structured data management, reduce administrative burdens, and support economic and regulatory objectives across the building life cycle.

#### 8.4.2.7 Summary business model canvas

Building on the preceding sections, which outlined potential configurations for each business model element, it becomes clear that DBPs offer a range of promising business model options. The logic of the Business Model Canvas provides a helpful structure to consolidate these considerations. Figure 8.5 visualizes a possible constellation of business model components, highlighting coherent and realistic choices for the development and commercialization of DBP applications.

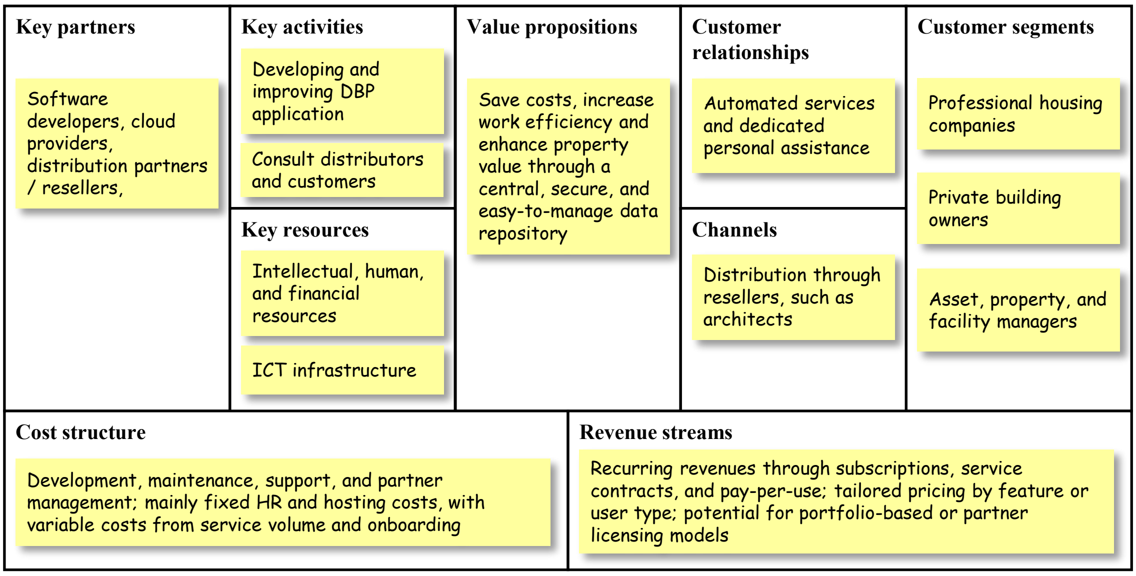



Figure 8.5: Example for a business model canvas for digital building passports

## 8.5 Actor-specific implementation

This section responds to a key implementation barrier raised in expert interviews: the lack of clarity on how a common framework for DBPs can be established while accounting for the diverse needs of actors. It highlights the importance of actor-based implementation and presents a general implementation process (section 8.5.1), followed by a classification of actor maturity levels (section 8.5.2) and corresponding solution strategies to support effective adoption across the real estate industry (section 8.5.3).

### 8.5.1 Universal implementation process

Implementing a DBP solution, whether for a single building or an entire building stock, often requires a substantial change process. To address this, a simple but universal implementation process is proposed, providing actors with a structured project management framework that can be adapted to specific scenarios. This process aims to support the successful adoption and operation of DBPs by offering guidance on key steps. Among other objectives, it seeks to:

- Ensure the success of the DBP implementation process.
- Guarantee that the DBP functions according to defined requirements.
- Define responsibilities and work packages for involved actors.
- Facilitate and enhance collaboration between DBP providers and purchasers.
- Generate learnings for future implementations.

The process consists of four main phases: initiation, preparation, launch, and monitoring (Figure 8.6). These phases are interconnected, allowing for fluid transitions; for example, tasks from the preparation phase may remain relevant during the launch or monitoring phases. Actors are encouraged to adapt this reference process, whether in a linear or non-linear (e.g., agile) approach, based on their specific needs.

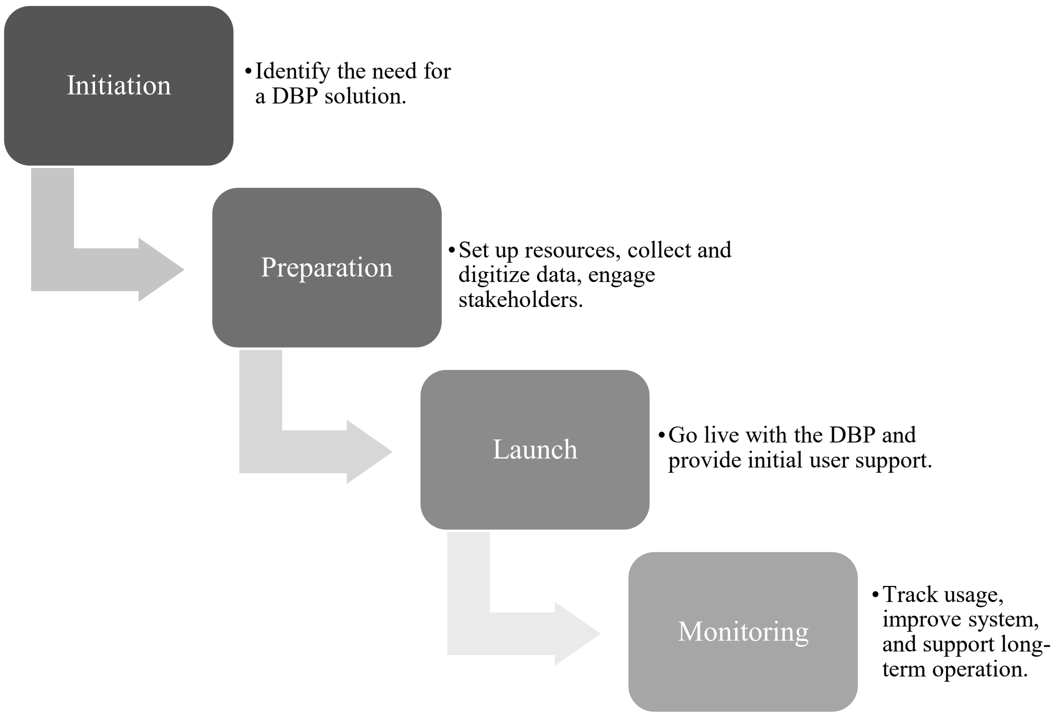



Figure 8.6: Universal implementation process for digital building passports

The *initiation phase* begins when an actor, such as a building owner, identifies a need for a DBP solution. This need may stem from challenges or opportunities related to:

- Real estate management throughout the building life cycle, such as missed targets or opportunities.
- Information management issues, including missing or poor-quality data and inefficient processes.
- Challenges in implementing BISs or information systems in general.
- Opportunities to enhance economic, environmental, or social performance through improved decision-making.

Motivations and expectations for DBPs vary by actor, influenced by individual circumstances. Purchasers require solutions aligned with their specific needs, while providers must communicate the functions and value of their DBP offerings transparently.

The *preparation phase* involves establishing the necessary organizational, data-related, technological, and financial resources to launch a DBP. A detailed inventory process, conducted in collaboration with the DBP provider, ensures that requirements, e.g. based on the requirement profile of this thesis (chapter 5), are met. Key tasks in this phase include:

- Identifying internal and external information sources to collect comprehensive building-related data.
- Engaging stakeholders across the building lifecycle, such as architects, service providers, and public authorities.
- Digitizing hardcopy documents to create machine-readable data, where possible.
- Collecting and cleansing data to achieve the quality required for integration into the DBP data model.
- Planning and managing the financial, human, and technological resources necessary for implementation and ongoing use.

This phase emphasizes collaboration between DBP purchasers and providers, with providers playing a key role in offering supportive services such as user training and data collection. A strategic plan should also be developed, outlining necessary steps, timelines, responsibilities, and barriers to manage during the launch.

The *launch phase* marks the point when the DBP solution goes live. While this phase can theoretically be reduced to a single moment, defining a distinct launch window can ensure sufficient resources are allocated to address potential challenges and facilitate user training. Feedback collected during this phase can be invaluable for both the purchaser and provider.

The *monitoring phase* begins once the launch phase concludes and extends indefinitely. The goal is to analyze the DBP's usage, identify areas for improvement, and implement necessary changes. Monitoring can address data, functions, processes, and ICTs, benefiting specific buildings, building stocks, or future implementations. This phase ensures the dynamic and evolving nature of DBPs is effectively managed, reinforcing their long-term value.

### 8.5.2 Levels of expertise and digital maturity

Potential users of DBPs are inherently heterogeneous, reflecting the diverse range of actors across the real estate industry that the system is intended to support. This diversity results from variations in organizational size, resource availability, degrees of specialization, and approaches to managing building-related information. While institutional real estate companies managing large portfolios often demonstrate advanced capabilities, including the use of BISs and proactive information management, smaller organizations or private building owners may operate with limited experience and fewer digital resources.

To address this heterogeneity, a classification is proposed that groups actors based on their expertise and digital maturity. The goal is twofold: First, to help real estate actors understand their own readiness and identify practical steps for DBP adoption. Second, to enable DBP providers and developers to design tailored solutions and onboarding strategies that reflect the needs of different user groups.

The classification framework considers five core dimensions: specialization in life cycle tasks, availability of building-related data, degree of data digitalization, availability of financial, human, and technological resources, experience with BISs.

The resulting maturity levels, summarized in Table 8.5, range from Level 0 (no readiness) to Level 5 (high digital maturity). Each level is characterized by typical actor profiles and a distinct combination of capabilities. This structure enables actors to assess their starting point, recognize their current gaps, and define a targeted transformation strategy. At the same time, it supports providers in aligning tools and processes with real-world user conditions.

Table 8.5: Classification of real estate actors by expertise and digital maturity

| Level | Degree of specialization in life cycle tasks | Availability of building-related data | Degree of digitalization (of data) | Availability of financial, human, technological resources | Experience in BIS use | Typical actors |
|---|---|---|---|---|---|---|
| 0 | zero | zero | zero | zero | zero | Actors that just start their role in the real estate industry |
| 1 | low | low | low | low | little | Private building owners, small non-profit-oriented companies |
| 2 | Low to medium | low | low | Medium to high | little | Privileged private building owners, lagging real estate companies |
| 3 | Low to medium | Medium to high | varying | low | little | Real estate companies with good information management but little resources, mostly small firms |
| 4 | Medium to high | Medium to high | varying | Medium to high | medium | Mostly large real estate companies with good information management and good availability of resources |
| 5 | high | high | high | high | Medium to high | Mostly large real estate companies (innovators, early adopters) |

Although actors may not fully align with a single level in practice, the classification offers sufficient granularity to guide both implementation planning and long-term digital development across the industry. As shown in Figure 8.7, regardless of their starting position in terms of specialization or available resources, actors can improve their digital maturity by focusing on increasing the availability, digitization, and overall quality of building-related data. This provides a foundation for more advanced applications and supports long-term readiness for DBPs.

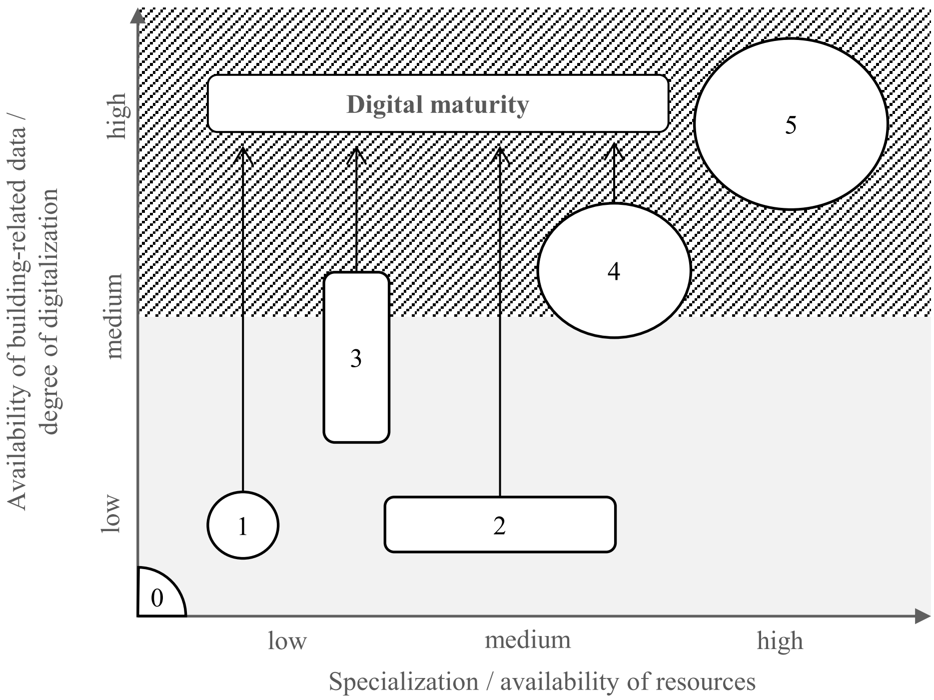



Figure 8.7: Transformation pathways for different actors to reach digital maturity

## 8.5.3 Tailored solution strategies based on actor maturity

The classification introduced in the previous section provides a structured basis for identifying the capabilities, needs, and constraints of different actor groups. This section builds on that foundation by outlining the types of DBP solutions best suited to each maturity level. It aims to support developers and providers in tailoring system design to real-world conditions across the real estate industry.

At 'Level 0', none of the defining characteristics are met. This category may include individuals entirely new to the real estate industry, such as first-time property owners. While these actors are unlikely to demand comprehensive digital solutions in the short term, basic tools that enable initial data collection and familiarization with digital formats can create future entry points. From a provider perspective, this level highlights the value of simple, low-effort offerings that require minimal input and no prior knowledge.

At ‘Level 1’, actors demonstrate low specialization, limited data availability, and minimal digitalization. Typical examples include private building owners or small non-profit organizations. For these users, providers should focus on straightforward, low-cost DBP solutions with minimal complexity. Such systems should enable basic data management and gradual engagement with digital information, laying the foundation for more advanced use over time.

At ‘Level 2’, actors such as municipal housing companies begin to engage with digitalization but often face internal barriers, including cultural resistance or a lack of process integration. For this group, providers should offer structured onboarding services, including basic training, guided implementation, and integration support. Incremental and modular system designs are especially valuable, as they allow gradual alignment with existing workflows and resource capacities.

At ‘Level 3’, actors typically possess some digital infrastructure and experience in information management but may operate with limited budgets or remain skeptical about the added value of new systems. Customizable and cost-transparent solutions are key at this level. Providers should demonstrate long-term value through use cases, reference projects, or return-on-investment arguments, while offering functionality that integrates well with existing tools.

At ‘Level 4’, organizations are digitally competent and have access to appropriate resources. These actors benefit most from solutions that emphasize interoperability, semantic data models, and integration with existing BISs. Providers should support internal capacity building and offer advanced features that align with organizational strategies, such as lifecycle cost analysis, sustainability reporting, or performance benchmarking.

At ‘Level 5’, actors are digitally mature and often drive innovation themselves. They typically seek highly customizable, advanced solutions, and may actively participate in system development. Providers should focus on co-development partnerships, support for emerging technologies (e.g., AI, IoT), and open interfaces for integrating specialized tools. These actors often serve as early adopters or reference users within the broader industry.

This maturity-based alignment of solution strategies provides a practical framework for supporting adoption across diverse actor groups. It allows providers to meet users where they are, while encouraging engagement with digital systems that are appropriate to their needs and capabilities.

## 8.6 Recommendations and further development

Building on the analysis and proposals presented in this thesis, this section provides targeted recommendations for supporting the further development, implementation, and long-term integration of DBPs. These recommendations address the perspectives of developers, users, public authorities, and researchers, offering practical guidance for improving DBP design, promoting adoption, and strengthening their role in life cycle-oriented information management. The structure reflects key areas of action: technical and strategic development 8.6.1, implementation practices (8.6.2), operational maintenance (8.6.3), regulatory support (8.6.4), and future research needs (8.6.5).

### 8.6.1 Design and development

Recommendations for the design and development of DBPs are grounded in the findings of this thesis and focus on practical guidance for developers. These are divided into tool-related aspects, which emphasize technical and functional considerations for LC-BISs, and business-related aspects.

DBPs should be developed with:

- Alignment with functional requirements: Focus on essential lifecycle tasks such as improving data governance, ensuring accessibility, and supporting decision-making, as defined in the requirement profile.
- Defined system boundaries and roles: Clarify the scope and responsibilities of the DBP within the broader system landscape to enhance usability and interoperability.
- Gradual migration pathways: Provide practical tools for transitioning from traditional portfolio management systems to DBPs, ensuring data consistency and improved granularity.
- Integration with complementary systems: Enable the DBP to function alongside existing BISs, including BIM and ERP, while maintaining focus on the unique roles of each system.
- Implementation of ISA elements: Prioritize the development of users, functions, data, ICTs, and processes, with a focus on robust data modeling, secure cloud-based infrastructures, and scalable system architectures.

Building on section 8.4, the business strategy for DBPs should emphasize creating value for users and enabling market adoption through targeted and adaptive approaches. Developers should:

- Focus on real estate companies as initial users: Engage expert actors who already manage extensive portfolios and have advanced information needs, providing a foundation for meaningful feedback and early adoption.
- Refine the value proposition: Offer solutions tailored to key pain points in information management, such as streamlining compliance or enhancing data quality.
- Gradually expand customer segments: Target additional users, such as public institutions or small-scale property owners, adapting the DBP offering to meet their specific needs.
- Utilize established industry networks: Leverage existing connections within the real estate and construction sectors for awareness-building, distribution, and support.
- Adopt flexible pricing and revenue strategies: Provide accessible entry-level pricing while offering advanced features or modules for additional fees, ensuring a broad appeal while maintaining profitability.
- Enhance customer engagement: Actively involve users in co-developing new functionalities and services, utilizing structured feedback mechanisms and collaborative initiatives.
- Encourage complementary partnerships: Collaborate with industry stakeholders, service providers, and technology developers to increase the DBP’s value proposition and market reach.
- Incorporate insights into automation: Streamline repetitive processes while balancing automation with personal assistance to enhance overall user satisfaction.

By addressing these structured recommendations, developers can create DBP solutions that are well-integrated, user-oriented, and aligned with the broader lifecycle management framework, while ensuring long-term sustainability in a competitive market.

### 8.6.2 Implementation and use

The implementation and use of DBPs should align closely with the transformation pathways outlined in Section 8.5, emphasizing a gradual, systematic approach to integrating DBPs into existing workflows and processes. DBP owners, particularly institutional users, are encouraged to build on the identified steps for transforming information management practices.

A central recommendation is to anchor DBP implementation in established organizational strategies for information management. This includes aligning the adoption of DBPs with ongoing efforts to enhance data governance, process efficiency, and decision-making across the building lifecycle. By focusing on strategic alignment, users can ensure that DBPs complement existing systems and organizational goals.

Implementation should proceed incrementally, leveraging structured pathways. Key actions include:

- Building necessary resources for DBP use: Allocate time, personnel, and technical infrastructure to support the integration of DBPs, ensuring readiness for adoption.
- Defining roles and responsibilities: Clearly assign tasks related to DBP management, ensuring effective coordination between internal teams and external service providers.
- Engaging stakeholders: Foster collaboration and buy-in from actors involved in the building life cycle, including external service providers.

For sustained use, owners should focus on maximizing the DBP's value by embedding its use in daily workflows and life cycle management processes. This includes:

- Fostering continuous improvement: Regularly update data, refine processes, and ensure the DBP remains a relevant and effective tool for decision-making.
- Identifying and leveraging use cases: Highlight specific scenarios where DBPs can deliver measurable benefits, such as compliance reporting, portfolio analysis, or maintenance planning.
- Encouraging innovation and feedback: Use structured mechanisms to collect user feedback, enabling iterative improvements and alignment with evolving needs.

To fully realize the potential of DBPs, owners should seek to integrate complementary technologies and approaches that enhance their utility. For example, integrating DBPs with building automation systems or energy monitoring tools can expand their capabilities and drive efficiency.

### 8.6.3 Maintenance and administration

The maintenance and administration of DBPs are critical for ensuring their long-term functionality, usability, and relevance. This section builds on the inherent DBP functions (section 7.2.2) specified in the thesis, while aiming to meet system-related requirements (section 5.6). Practical recommendations are given for DBP owners and service providers responsible for sustaining the system throughout its life cycle.

Effective maintenance begins with the establishment of clear management frameworks that address preventive maintenance, error handling, and system updates. Service providers and DBP owners should adopt standardized procedures that ensure continuity and adaptability. Key steps include:

- Implementing preventive maintenance processes: Proactively monitor and address potential issues to minimize disruptions and maintain system reliability.
- Standardizing error handling: Develop agile procedures for identifying, categorizing, and resolving errors, tailored to their type and impact.
- Regularly updating security measures: Stay ahead of emerging threats by continuously enhancing data protection, user authentication protocols, and system defenses.

To support users and foster engagement, DBP service providers should offer a range of support services and communication channels. These efforts should include:

- Providing guidance and training: Ensure that DBP users are equipped with the knowledge and skills required to effectively utilize and maintain the system.
- Establishing customer support mechanisms: Create responsive help desks or online platforms for addressing user queries and issues promptly.
- Incorporating user feedback: Actively engage users in the system's development by incorporating their input into updates and enhancements.

Collaboration between DBP owners and developers is essential for leveraging synergies and ensuring that the system evolves to meet changing requirements. Recommendations include:

- Coordinating updates and upgrades: Work closely with developers to roll out new features, ensuring compatibility and minimizing disruption.
- Aligning maintenance efforts with lifecycle needs: Tailor administrative activities to the building's lifecycle stages, such as renovations or changes in ownership.
- Exploring complementary business models: Identify opportunities for service providers to offer maintenance-related services, such as data quality management, application updates, or stakeholder coordination, as value-added offerings.

Ultimately, the goal of maintenance and administration is to sustain the DBP's relevance and functionality while fostering trust among users. By adopting structured processes and collaborative practices, DBP owners and service providers can ensure the system remains a reliable and effective tool for lifecycle-oriented information management.

### 8.6.4 Regulation

Regulation plays a crucial role in fostering the adoption and effective use of DBPs. Governments and public authorities are in a unique position to establish a framework that supports innovation while ensuring trust and compliance. A key priority is the creation of clear legal foundations that address the ownership, privacy, and security of building-related data. By defining the rights and responsibilities of actors, regulation can build trust in data governance and promote transparency. Such frameworks should also ensure alignment with existing data protection laws, such as GDPR where applicable, and provide guidelines for preventing data misuse.

To foster collaboration and data sharing, regulations should promote standardized mechanisms to ensure interoperability and accessibility. Incentives such as financial support or recognition programs can encourage organizations to adopt DBPs and contribute to data ecosystems. Key measures include:

- Encouraging data sharing through clear protocols and governance structures that prevent misuse while enabling efficient exchange.
- Providing incentives for organizations that adopt and integrate DBPs into their workflows, such as grants, tax benefits, or public recognition.

Public authorities themselves can lead by example by integrating DBPs into their workflows. For instance, DBPs can be used as gateways for digitizing building permit processes, streamlining communication and data exchange between builders and regulatory agencies. They can also support the creation of comprehensive national databases on building stocks, valuable for urban planning, sustainability initiatives, and evidence-based policy-making.

Standardization efforts are another critical aspect of effective regulation. Policymakers should work with industry stakeholders to ensure:

- Minimum requirements for data content and functionality, ensuring that DBPs operate consistently across different use cases. The taxonomy of building-related data needs developed in chapter 3 as well as other proposals such as the requirement profile for LC-BISs and the ISA can serve as good starting points.
- Procedural guidelines for their implementation, including roles and responsibilities for various actors.
- Clear differentiation from other digital tools, preventing redundancy and clarifying the unique purpose of DBPs.

By combining clear legal frameworks, incentivized collaboration, public sector leadership, and standardized requirements, regulations can provide the foundation for DBPs to thrive as a tool for lifecycle-oriented information management. These efforts will not only build trust but also ensure that DBPs contribute to broader societal goals, such as sustainability, efficiency, and improved governance in the built environment.

### 8.6.5 Research

Research plays a vital role in addressing the challenges and opportunities associated with DBPs. Advancing their development, implementation, and adoption requires interdisciplinary and targeted research efforts that bridge the gap between theory and practice. This section outlines key areas where researchers, academic institutions, and research-supporting organizations can contribute to the successful evolution of DBPs.

A primary focus of research should be on identifying and addressing gaps in building-related information management. This includes exploring the practical challenges faced by various actors in managing data and understanding its value. Key research priorities include:

- Information management challenges: Investigate how actors manage building-related data, including barriers to effective governance and opportunities for improvement.
- Valuation of data and information: Develop methods to quantify the economic value, risks, and benefits of data, enabling better decision-making and resource allocation.

The potential of emerging technologies for DBPs is another crucial area of inquiry. Researchers should explore the integration of advanced technologies, such as artificial intelligence, semantic modeling, and blockchain, to enhance DBP functionality. Emphasis should be placed on their feasibility, scalability, and ability to address lifecycle-oriented use cases.

To ensure practical relevance, research should focus on the application of DBPs in real-world contexts. This includes conducting empirical studies to evaluate current practices and exploring innovative solutions to address existing limitations. Examples of practical topics include:

- Use case development: Identify specific scenarios where DBPs can deliver measurable benefits, such as predictive maintenance, compliance reporting, or energy optimization.
- Interoperability solutions: Investigate how DBPs can function alongside other systems, ensuring seamless data exchange and integration.

Standardization and best practices also require significant attention. Researchers can support policymakers and industry stakeholders by providing evidence-based recommendations for defining minimum requirements, procedural guidelines, and use case scenarios for DBPs.

Lastly, research efforts should adopt a holistic and interdisciplinary approach to ensure that solutions are robust and applicable across a wide range of contexts. Collaboration across disciplines and between academia, industry, and public authorities is essential to drive innovation and ensure that DBPs fulfill their potential as transformative tools for lifecycle-oriented information management.

By addressing these research priorities, the academic community can contribute to overcoming the barriers to DBP adoption and development while ensuring that these systems remain aligned with the evolving needs of the built environment.

# 9 Conclusion and outlook

## 9.1 Summary of findings

Within this thesis, a strong foundation could be laid for the future investigation, development, and implementation of LC-BISs against the background of information management in the real estate industry. By systematically dealing with both the basics and the details of how LC-BISs can serve as an impactful tool, this thesis approached a research gap from different perspectives: On the one hand, more clarity could be brought into the aspects of a concept, which is in discussion for so long at the brick of theory, practice, and politics. While the latest developments in the field have an impact on stressing the importance of life cycle information management, they also lead to confusion, especially among practitioners. One reason is that numerous initiators follow the phenomenon of "passportization" with more and more proposals for tools with a specific functionality. Within this thesis, the differences and similarities between these tools could be pointed out, while digital building passports serving as the key tool to serve as interoperable LC-BISs.

On the other hand, this thesis can be regarded as a foundational work for the field of information management in the built environment, still a niche in research with a strong increase in importance. While the gap for a systematic analysis of information needs in the context of LC-BISs could be closed, the author made one step further towards interdisciplinarity in real estate research by integrating the perspectives of business informatics, a discipline that plays a key role in digitalization and automation at the interface of theory and practice.

To further summarize the findings of this thesis, it will be explained how the research questions posed in section 1.3 could be answered.

(1) What requirements must a system meet to function as a Life Cycle Building Information System (LC-BIS), considering building-related data needs, information management challenges, and digital solutions?

In order to answer this question, a fundamental perspective was taken on information management in the real estate industry (chapter 3), building on the foundational considerations introduced in chapter 2. First, a definition of the term "building-related data" was derived. So far, there is no universal definition in the real estate industry due to different interpretations of what constitutes a building and misconceptions on data. The given definition therefore was built on the core definitions of the two terms, providing essential boundaries for the concept but still leaving room to specify building-related data more clearly. It was explained that, throughout this thesis, the term was mainly used to refer to data on a single building level.

After explaining when building-related data are primarily created throughout the life cycle, types of building-related data were discussed. It was observed that there are several criteria to classify building-related data, for example into static vs dynamic, alphanumeric vs geometric, or structured vs unstructured. Also, the differences between aggregated data, which can be very useful to describe building quality characteristics, and raw data, relevant in the form of building properties and attributes was explained. The different types of data mark an important basis to specify data quality requirements.

To receive a better understanding on how building-related data actually arise, relevant data creation and collection methods were investigated. Special focus was laid on data collection by providing essential basics first before analyzing relevant data collection methods in the real estate industry. In addition, important regulatory systems for data creation and collection covering legal requirements and standards to analyze to which extent these processes are built standardized conventions.

The core of chapter 3 was the task-oriented analysis of data needs. First, the decision context of actors was analyzed to better comprehend the role of building-related data for actors. Decisions are often complex and not always rational. A substantial amount of occasions in which actors require building-related data could be identified. Then, a step-by-step analysis was carried out to determine the data needs throughout the life cycle of buildings. A selection was made of relevant tasks that tried to cover building-related data needs holistically, also in respect to potential future data needs, while still being clear. For each task area, suitable information sources were analyzed covering research results, industry standards, and legal requirements. The result was recorded in a condensed taxonomy of building-related data needs using a simple but yet effective classification into master data, inventory data, economic and legal data, and performance data. A 3-digit enumeration system was applied to ensure a structured overview. It shows the abundance of relevant data points, but also the possibility to concentrate on overarching categories. This result provided a strong foundation to determine requirements on a LC-BIS. The methodology marks a new approach that decouples from the focus on actor roles, as present in former studies, which is not suited anymore in times of dynamically changing actor roles and constellations.

Chapter 3 was complemented by an analysis of why the identified data needs are typically not satisfied within the real estate industry. A classification was made to structure typical issues that impede the information management of actors with the lack of needed data in the right quality as a substantial problem. In addition, critical points in the building life cycle, industry-specific barriers, and typical phenomena as explained by principal-agent-theory were examined. The classification served to systematically derive potential areas of improvement. As one of these areas, the use of BISs was identified which have the potential to tackle information management issues in a multi-dimensional way.

The analysis of requirements on LC-BIS was continued in chapter 4 with an analysis of the potentials of modern ICT to provide solutions to important information management aspects including data collection, storage, sharing, quality management, analytics, and security. For all of these aspects, specific fundamentals, the current state and implementation within the real estate industry, and their potentials and limitations were examined. Insights include:

- Data collection: Original data collection, especially collection of geometric data, is cost-intensive and requires specialized equipment. A smooth transfer of these data into LC-BISs is crucial. Secondary data collection methods in connection with automated processing capacities, for example with the help of OCR and AI, gain importance and provide promising opportunities to access data efficiently.

- Data storage: LC-BISs must increasingly operate with decentralized data storage paradigms to serve actor constellations. Cloud architectures offer scalable and flexible options for most use cases.
- Data sharing: Structured data formats, such as XML, JSON, or IFC, offer great potentials to leverage the analytical potential of data but also pose strict requirements. Linked data approaches emerge in the industry to provide more flexibility, but are not yet established. Platforms and data rooms are gaining relevance since they combine several technologies to simplify data sharing between actors.
- Data quality management: It could be observed that the management of data quality is complex and that there is no ICT that can cover this task alone. A mixture of actions is needed which need to be considered in BIS design.
- Data analytics: There are a lot of potentially beneficial use cases for data analytics, often based on AI and ML mechanisms, in the building life cycle. One of the biggest challenges however is to ensure the data quality required for these approaches.
- Data security: BISs need profound solutions for access controlling and data ownership management. Several options could be discussed including their advantages and disadvantages. Blockchain technology is gaining prominence in the real estate industry and can potentially serve as a good addition to BISs to establish immutable building records.

In addition to the potentials, the analysis emphasized relevant features that these technologies enable when applied in an information system. This included the systems' reliability, scalability, and interoperability.

The insights of chapters 3 and 4 were used to specify a profound requirement profile in chapter 5. A definition of a LC-BIS was given to provide the basis for specifying core functions, system boundaries, requirements on the overall usefulness. Hence, the most important function of a LC-BIS is to work as a building-related data repository, but a simultaneous usage as documentation aid, data quality management tool, and platform for data sharing is beneficial as well. Actor-specific requirements on such a tool were summarized and the desired data content was specified. In addition to referencing the data needs, as identified in chapter 3, the inclusion of different types of data was stressed covering raw data, aggregated data, documents, linked data, and metadata. In addition, requirements on data quality and system functionality were posed. The essence of the requirements on a LC-BIS was captured in a fact sheet that served as the foundation to test the suitability of existing BISs as LC-BIS in the following chapter.

(2) Which types of BISs play a role in managing building-related information in theory and practice, and to what extent do they fulfill the requirements of a LC-BIS?

To answer this question, a systematic literature review was carried out with the aim to identify BISs with a potential to serve as LC-BISs (chapter 6). The methodology builds on the PRISMA framework. Since the field of BISs in the real estate industry is very broad, different sources were used including scientific literature, grey literature, such as industry and policy reports, and the perspectives of practitioners based on expert interviews. After carrying out the initial research with the determination of a search string and evaluating the results of the literature review quantitively, it was decided to analyze relevant BISs in functional groups. These included:

- Building passports, logbooks, and files: This group of systems already exists for long, but, while not finding wide adoption in the industry yet, are significantly gaining popularity again through new initiatives and proposals for their adoption as digital tools. It was found that despite insufficiencies in existing approaches and a strong fragmentation of proposals, their original intent comes very close to the concept of LC-BISs.
- Topical passport schemes: The phenomenon of "passportization" has led to a number of other systems under this terminology. This includes material passports, which basically aim to provide a material inventory throughout the building life cycle, and renovation passports, which should give actionable advice on potential renovation measures to owners. Both aspects are relevant for LC-BISs topical-wise but the systems alone do not meet the requirements of a LC-BIS.
- Virtual building models: The big advantage of BIM and digital twin applications lies in their capability of visualizing the geometry of buildings and offering a structured approach to manage and make use of building-related data throughout many use cases. Thus, they are suited as LC-BISs very well. However, they also require substantial expertise and upfront costs, which is one reason why they are (still) not suited for the majority of practitioners.
- Building information systems with a more specific scope: This group of tools, for example including facility management systems and building registers, is originally not intended to serve as LC-BISs, but they increasingly cover building-related data more comprehensive and take in important roles for actors.

It was found that, while almost all systems tend to move to a higher density of building-related data, most of them have a more specific focus on predefined tasks or data points. The group of building passports, logbooks, and files was identified as most suited to meet the functionality of a LC-BIS. It was therefore decided to specify DBPs as LC-BIS.

(3) How can a common framework be designed to meet the information management requirements of LC-BISs, and how can it support their practical development and implementation?

In order to derive a common framework for LC-BISs, their underlying character as an information system was considered. A proposal was made for an ISA that covers and structures all major elements of a DBP in its role as LC-BIS. These elements which include the functions, data, users, ICTs, and processes of such a system, lay the groundwork to comprehensively specify its functionality. The ISA was visualized in an architecture model, while intersections to the external environment of the system were specified through system boundaries. The model for the ISA was used to step-by-step derive models and architectures for the specific views of elements. This included:

- The specification of inherent and built-up functions with the help of a function tree: Inherent functions refer to (administrative) tasks that need to be carried out to ensure the basic functionality of the system including the management of users, technologies, and processes. Built-up functions show what the system can do for the user. Here, the proposal translates the requirements from the requirement profile into statically defined functions. These functions become "alive" by integrating them with other elements of the ISA in a process. In order to show the practical relevance of these abstract functions, relevant use cases were described.

- The showcasing of suitable data modeling approaches: Based on the taxonomy of building-related data needs, the necessary data content was specified. In addition, different data modeling approaches were proposed depending on the contextual use case. Ontology-based approaches were highlighted as a modern and powerful option, especially in connection with linked data implementations, while non-expert domains might still rely more on a less structured data model as indicated by the taxonomy of data needs.
- A user model, which specified relevant user information in the system. It lays the groundwork for implementing an access strategy, a data ownership model, and personalization to enhance usability. It was proposed to primarily focus on a RBAC model to ensure controlled access and security as well as a decentralized data ownership approach so that users remain in control over their data and develop trust into the system.
- A technology framework that specifies the most important technologies for LC-BISs. A three-tier architecture is proposed with a cloud architecture and security measures functioning as core technologies. The architecture enables a modular employment and enhancement with additional technologies, such as microservices, linked data, blockchain, and APIs. Conceptual proposals on how these technologies can be integrated were given.
- A process model integrating all other elements to ensure the functionality of the system. In addition to explaining internal information flows within the system, a job-sharing approach with other BISs was made. In addition, a process modeling approach was chosen to showcase how the system operates and how it integrates the different elements of the system.

By structuring a DBP in this way, a strong foundation was created for practical implementations that has its focus on semantics but considers technical views as well. In addition, the gap between fragmented ideas for the functionality of DBPs, formed within recent years, and a holistic conceptualization could be closed.

In order to assess the possibilities for a practical implementation of DBP, as specified in chapter 7, a best-case scenario for implementation throughout the life cycle was specified at the beginning of chapter 8. This scenario combined an optimal use of DBPs to improve information management in the life cycle with the functionality of the ISA and other proposals within this thesis in this regard. Based on this and with the help of expert interviews, the proposals were validated. Potentials as well as barriers and challenges were discussed. Two substantial barriers were identified in the economically viable implementation as well as the low level of expertise and digitization among practitioners. In order to address the crucial aspect of economic viability of such a tool, different economic implementation options were discussed first before elaborating on elements of potential business models. In order to provide actionable advice on how to implement DBPs, actor-specific transformation pathways were developed considering their level of expertise and digital maturity. Finally, a condensed list of advices was created for the main addressees of this thesis including practitioners, regulators, and researchers.

## 9.2 Limitations

While this thesis provides a valuable contribution to the field of information management in the real estate industry and its connection to BISs, it is subject to several limitations. These can be categorized into methodological, practical, content-related, and contextual constraints.

*Methodological limitations*: To address the diverse research questions posed, a mix of methods was employed. However, this approach carries inherent limitations. Thematically, the thesis delves into a niche field of research, focusing on information management for single buildings and its connection to BISs, a subject that has received limited explicit attention in the literature. This nascent state of the research field required building on a narrow foundation, which, while challenging, also allowed the thesis to pioneer an interdisciplinary perspective that bridges the BIM, informatics, and building ownership domains.

The selection of literature for analyzing information management in the real estate industry and the potentials of ICT reflects the author's expertise and perspective. Despite efforts to adopt a holistic approach and integrate expert interviews, the structure and prioritization of content remain subjective and debatable. Similarly, the systematic review of existing BISs aimed to provide an unbiased and representative analysis by incorporating both theoretical and practical viewpoints. However, the breadth of approaches in theory and practice made it impossible to include all potential variants, particularly concerning system-specific implementations.

Data collection was further limited when addressing barriers, economic considerations, and actor-specific implementation options. While realistic scenarios were discussed to provide actionable insights, the exploration of alternative scenarios and deeper practical nuances was constrained by the available data and scope of the study.

Analytical limitations also emerged, particularly in deducing information needs from diverse literature and generalizing information management problems into categories. While these analyses provide valuable insights, their broad scope and complexity leave room for further exploration. Similarly, the requirement profile for LC-BISs was developed based partly on hypotheses and general consensus, aligning with literature but influenced by the author's focus and interpretation.

*Practical limitations*: This thesis aimed to address a specific research gap holistically. However, given the scope and nature of the study, the research could only provide qualitative and conceptual insights. Practical development, such as creating a prototype for the proposed models or systems, was not feasible within the constraints of this work. Developing a prototype would require additional skills, resources, and a more focused scope, which could risk narrowing the interdisciplinary perspective prioritized in this research.

*Content-related limitations*: Certain limitations also pertain to the content of this thesis, influenced by practical and methodological constraints. The broad scope of information management and BISs in the real estate industry meant that not all aspects could be covered in detail. Decisions on the level of abstraction were made contextually throughout the thesis, leading to constraints in areas such as:

- Specifying data needs across the building life cycle, where the condensed list of data points could be endlessly detailed.
- Elaborating on information management problems, which could constitute a separate research focus.
- Avoiding overly detailed descriptions of ICT fundamentals to maintain relevance to the study's goals.
- Detailing all aspects or possibilities relevant to ensuring data and system quality in a LC-BIS.
- Detailing specific BIS functions identified in the literature review.
- Developing overly detailed submodels within the ISA in the results section
- Discussing all potential dimensions relevant for DBP implementation.

These limitations were carefully chosen, weighing the costs and benefits of additional detail. In some cases, such as developing a semantic data model or a comprehensive process model for DBPs, the complexity would exceed the scope of this thesis and require the resources of a dedicated research project.

*Contextual limitations*: The findings of this thesis are primarily applicable to the European, particularly German, context. This focus reflects the predominance of relevant literature, expert input, and the author's background. While the research offers globally relevant insights, other regions may require different focal points and functionalities in tools such as DBPs.

Temporally, the dynamic nature of the field also imposes limitations. Developments in politics, regulations, and digitalization may render some findings outdated over time. Nevertheless, the European and German perspective was intentionally chosen to provide targeted assistance in these contexts.

By acknowledging these limitations, the thesis highlights the complexity of the research field while emphasizing its contributions. These constraints also present opportunities for future research to deepen and expand on the insights provided, fostering further development in this interdisciplinary domain.

## 9.3 Outlook

This thesis has laid a substantial foundation for clarifying the premises and functionality of DBPs. While providing valuable insights, it also highlights several areas that warrant further exploration, practical application, and broader contextual consideration.

*Future research directions* include the continuous exploration of emerging technologies and the potential of digitization and automation in streamlining information management processes. Future studies could focus specifically on the interfaces and synergy effects of combining different technologies to enhance the use case of DBPs. Additionally, there is a need for more actor-specific research to better understand the diverse requirements of actors in information management, both generally and in relation to DBPs. While highly advanced concepts and technologies are essential to push boundaries, research must also bridge the gap to actors with fewer resources or lower levels of expertise. Investigations could explore pathways to support these actors, either by guiding them toward adopting advanced solutions or by identifying practical, achievable alternatives that align with their capabilities.

*Practical implications* were outlined in section 8.6, where several actionable proposals were presented for advancing the use, development, and implementation of DBPs, addressing the roles of theory, practice, and policy. Close collaboration between the various actor groups will be crucial for progress in this domain. It is vital that all actors, solution providers, practitioners, policymakers, and others, can clearly identify their roles and contributions to further advancements. The findings of this research offer a robust foundation enabling them to better understand DBP functions and leverage their benefits.

For policymakers, this thesis serves as a tool to comprehend the potential of DBPs as a policy instrument, paving the way for their adoption in strategies aimed at improving information management in the built environment. Beyond this, the work may prove particularly relevant for standardization efforts concerning DBPs. The taxonomy of building-related data developed herein adopts a classification logic familiar to the industry, similar, for instance, to the structure of DIN 276 (building costs). Further standardization could also focus on core DBP functions and how they are to be applied consistently across building life cycle stages.

This research is situated at the intersection of ongoing megatrends, thematically and temporally. It demonstrates the role of interdisciplinary research, particularly the application of business informatics, to address a research gap within the real estate industry. Digitalization serves as both a boundary condition for this field and a target for improvement, with the results of this thesis contributing to the broader goal of enhancing digital transformation in the built environment. Similarly, sustainability, while not the original focus of this research, is a driving force shaping the requirements for information management in the built environment. Robust solutions like DBPs can play a significant role in advancing sustainable practices by enabling better decision-making, resource optimization, and transparency across the building life cycle.

Looking ahead, DBPs hold the potential to substantially improve key tasks in real estate management. Based on the results of this thesis, future applications may include:

- Streamlining construction documentation
- Standardizing and digitizing building handover
- Facilitating transparent real estate marketing
- Supporting asset management throughout the life cycle while informing long-term renovation planning and deconstruction
- Enabling automated property valuation, risk assessments, and performance assessments

These examples underline the practical relevance of DBPs and their capacity to support data-driven decision-making across the building life cycle.

Achieving widespread adoption of DBPs in the functionality proposed in this thesis presents notable challenges and risks. Effective, efficient, and economically viable implementation of these tools will require concerted effort and commitment from all actors involved. While the concepts and technologies exist, and the will to improve is evident, the collaboration and coordination necessary to achieve this vision remain a complex task.

Nevertheless, the author is optimistic that even small steps in the right direction will gradually lead to DBPs becoming the *transformative tools* they are intended to be, unlocking their full potential in advancing information management and sustainable practices within the built environment.

# References


Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*, 103299. https://doi.org/10.1016/j.jobe.2021.103299

Ackoff, R. L. (1989). From data to wisdom. *Journal of Applied Systems Analysis*, *16*, 3–9.

Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies*, *14*(8), 2289. https://doi.org/10.3390/en14082289

Adlington, G., Lamb, T., Mclaren, R., & Tonchovska, R. (2021). *Insights into real estate registration and cadastre*. Royal Institution of Chartered Surveyors (RICS).

Aggarwal, C. C. (2015). *Data Mining: The textbook*. Springer International Publishing. https://doi.org/10.1007/978-3-319-14142-8

Akbarieh, A., Jayasinghe, L. B., Waldmann, D., & Teferle, F. N. (2020). BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. *Sustainability (Switzerland)*, *12*(7), 2670. https://doi.org/10.3390/su12072670

Akinade, O. O., Oyedele, L. O., Omoteso, K., Ajayi, S. O., Bilal, M., Owolabi, H. A., Alaka, H. A., Ayris, L., & Henry Looney, J. (2017). BIM-based deconstruction tool: Towards essential functionalities. *International Journal of Sustainable Built Environment*, *6*(1), 260–271. https://doi.org/10.1016/j.ijsbe.2017.01.002

Alda, W., & Hirschner, J. (2016). *Projektentwicklung in der Immobilienwirtschaft*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-13930-8

Alexopoulos, P. (2020). *Semantic modeling for data: Avoiding pitfalls and breaking dilemmas*. O'Reilly.

Almukhtar, A., Saeed, Z. O., Abanda, H., & Tah, J. H. M. (2021). Reality Capture of Buildings Using 3D Laser Scanners. *CivilEng*, *2*(1), 214–235. https://doi.org/10.3390/civileng2010012

Alonso, R., Olivadese, R., Ibba, A., & Reforgiato Recupero, D. (2023). Towards the definition of a European Digital Building Logbook: A survey. *Heliyon*, *9*(9). https://doi.org/10.1016/j.heliyon.2023.e19285

Alpar, P., Alt, R., Bensberg, F., & Weimann, P. (2019). *Anwendungsorientierte Wirtschaftsinformatik*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-25581-7

Alreshidi, E., Mourshed, M., & Rezgui, Y. (2016). Cloud-Based BIM Governance Platform Requirements and Specifications: Software Engineering Approach Using BPMN and UML. *Journal of Computing in Civil Engineering*, *30*(4), Article 04015063. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000539

Al-Sadoon, N., Fauth, J., & Menzel, K. (2023). Digital Twins as Enabler for Long Term Data Management Using Building Logbooks. In L. M. Camarinha-Matos, X. Boucher, & A. Ortiz (Eds.), *IFIP Advances in Information and Communication Technology: Vol. 688, Collaborative Networks in Digitalization and Society 5.0: 24th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2023, Valencia, Spain, September 27–29, 2023, Proceedings* (pp. 673–686). Springer Nature Switzerland; Imprint Springer. https://doi.org/10.1007/978-3-031-42622-3_48

Andreoli, A., Lounis, A., Debbabi, M., & Hanna, A. (2023). On the prevalence of software supply chain attacks: Empirical study and investigative framework. *Forensic Science International: Digital Investigation*, *44*, 301508. https://doi.org/10.1016/j.fsidi.2023.301508

Arabshahi, M., Di Wang, Sun, J., Rahnamayiezekavat, P., Tang, W., Wang, Y., & Wang, X. (2021). Review on Sensing Technology Adoption in the Construction Industry. *Sensors (Basel, Switzerland)*, *21*(24), 8307. https://doi.org/10.3390/s21248307

Araszkiewicz, K. (2017). Digital Technologies in Facility Management – The state of Practice and Research Challenges. *Procedia Engineering*, *196*, 1034–1042. https://doi.org/10.1016/j.proeng.2017.08.059

Arbeitskreis Maschinen- und Elektrotechnik staatlicher und kommunaler Verwaltungen. (2020). *Technisches Monitoring 2020: Technisches Monitoring als Instrument zur Qualitätssicherung.*

Arens, J. (2016). Unterscheidung nach Immobilienarten. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed.). De Gruyter Oldenbourg.

Asswad, J., & Marx Gómez, J. (2021). Data Ownership: A Survey. *Information*, *12*(11), 465. https://doi.org/10.3390/info12110465

Atlan. (2025, March 29). *Data Governance Models: Centralized, Decentralized, Federated*. https://atlan.com/know/data-governance/data-governance-models/

Atta, N., & Talamo, C. (2020). Digital Transformation in Facility Management (FM). Iot and Big Data for Service Innovation. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Springer eBook Collection. Digital Transformation of the Design, Construction and Management Processes of the Built Environment* (pp. 267–278). Springer International Publishing.

Auer, F., Lenarduzzi, V., Felderer, M., & Taibi, D. (2021). From monolithic systems to Microservices: An assessment framework. *Information and Software Technology*, *137*, 106600. https://doi.org/10.1016/j.infsof.2021.106600

Auer, T., Bell, D., Briels, D., Granmayeh, A., Gruber, E., Huber, M., Laus, L., Lipp, B., Meier, A., Muñoz-Czerny, U., Rink, A., Schmitteckert, L., Vidovic, P., Zelger, T., & Lammers, J. (2024). *Lowtech-Forschungsprojekte: Nutzerkomfort durch Lowtech Konzepte in Gebäuden : robuste, nutzerfreundliche und kostengünstige TGA in Gebäuden : sommerlicher thermischer Komfort - Neuformulierung der "Klimarichtlinie" für Bauprojekte des Bundes*. *Schriftenreihe Zukunft Bauen: Band 34*. Bundesinstitut für Bau- Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR). https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/zukunft-bauen-fp/2024/band-34-dl.pdf

Ausschuss der Verbände und Kammern der Ingenieure und Architekten für die Honorarordnung. (2020). *Projektmanagement in der Bau- und Immobilienwirtschaft - Standards für Leistungen und Vergütung: Leistungsbild und Honorierung* (5.th ed.). *AHO-Schriftenreihe: Nr. 9*. Reguvis Kooperationspartner des Bundesanzeiger Verlages.

Awadid, A., Nurcan, S., & Ghannouchi, S. A. (2017). Towards a Decision-Support System for Selecting the Appropriate Business Process Modeling Formalism: A Context-Aware Roadmap. In I. Reinhartz-Berger, J. Gulden, S. Nurcan, W. Guédria, & P. Bera (Eds.), *Springer eBook Collection Business and Management: Vol. 287. Enterprise, Business-Process and Information Systems Modeling: 18th International Conference, BPMDS 2017, 22nd International Conference, EMMSAD 2017, Held at CAiSE 2017, Essen, Germany, June 12-13, 2017, Proceedings* (Vol. 287, pp. 239–256). Springer. https://doi.org/10.1007/978-3-319-59466-8_15

Awolusi, I., Marks, E., & Hallowell, M. (2018). Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Automation in Construction*, *85*, 96–106. https://doi.org/10.1016/j.autcon.2017.10.010

Azmi, A., Ibrahim, R., Abdul Ghafar, M., & Rashidi, A. (2022). Smarter real estate marketing using virtual reality to influence potential homebuyers' emotions and purchase intention. *Smart and Sustainable Built Environment*, *11*(4), 870–890. https://doi.org/10.1108/SASBE-03-2021-0056

Baars, H., & Kemper, H.-G. (2021). *Business Intelligence & Analytics – Grundlagen und praktische Anwendungen*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-8348-2344-1

Baduge, S. K., Thilakarathna, S., Perera, J. S., Arashpour, M., Sharafi, P., Teodosio, B., Shringi, A., & Mendis, P. (2022). Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Automation in Construction*, *141*, 104440. https://doi.org/10.1016/j.autcon.2022.104440

Barkley, L. (2001). Key performance indicators: Primary drivers of information systems design. *Journal of Corporate Real Estate*, *3*(2), 161–171. https://doi.org/10.1108/14630010110811553

Bartels, N. (2020). *Strukturmodell zum Datenaustausch im Facility Management*. *Baubetriebswesen und Bauverfahrenstechnik*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-30830-8

BASTA. (2023, May 31). *Logbook service functions*. https://www.bastaonline.se/en/digital-tools/logbook-service/functions

Batini, C., Cappiello, C., Francalanci, C., & Maurino, A. (2009). Methodologies for data quality assessment and improvement. *ACM Computing Surveys*, *41*(3), 1–52. https://doi.org/10.1145/1541880.1541883

Batini, C., & Scannapieco, M. (2016). *Data and information quality: Dimensions, principles and techniques*. *Data-centric systems and applications*. Springer International Publishing AG.

Beach, T., Petri, I., Rezgui, Y., & Rana, O. (2017). Management of Collaborative BIM Data by Federating Distributed BIM Models. *Journal of Computing in Civil Engineering*, *31*(4), Article 04017009. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000657

Becker, J., Probandt, W., & Vering, O. (2012). *Grundsätze ordnungsmäßiger Modellierung*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-30412-5

Becker, M., & Bröcker, J.-O. (2021). *Business Model Canvas - Wesentliche Vor- und Nachteile im Überblick* (IUCF Working Paper 5/2021). Kiel, Hamburg: ZBW - Leibniz Information Centre for Economics. https://www.econstor.eu/handle/10419/234962

Bello, S. A., Oyedele, L. O., Akinade, O. O., Bilal, M., Davila Delgado, J. M., Akanbi, L. A., Ajayi, A. O., & Owolabi, H. A. (2021). Cloud computing in construction industry: Use cases, benefits and challenges. *Automation in Construction*, *122*, 103441. https://doi.org/10.1016/j.autcon.2020.103441

Bergman, M. (2009). Advantages and Myths of RDF. https://www.mkbergman.com/wp-content/themes/ai3v2/files/2009Posts/Advantages_Myths_RDF_090422.pdf

Bergmeister, K., Strauss, A., & Hoffmann, M. (2022). Digitale Zustandserfassung von Gebäuden, Infrastrukturbauwerken und Naturgefahren. In K. Bergmeister, F. Fingerloos, & J.-D. Wörner (Eds.), *Beton-Kalender: 111. Jahrgang (2022). BetonKalender 2022* (111. Jahrgang, Vol. 596, pp. 533–606). Wiley. https://doi.org/10.1002/9783433610879.ch8

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, *30*(3), 500–521. https://doi.org/10.1016/j.aei.2016.07.001

Blampain, F., Bricogne, M., Eynard, B., Bricogne, C., & Pinon, S. (2023). *Digital Thread and Building Lifecycle Management for Industrialisation of Construction Operations: A State-of-the-Art Review. Lecture Notes in Mechanical Engineering.* https://doi.org/10.1007/978-3-031-15928-2_77

Blum, A. (2001a). „Building-Passport" – A Tool for Quality, Environmental Awareness and Performance in the Building Sector. *OECD/IEA Joint Workshop on the Design of Sustainable Building Policies - Summary and Conclusions and Contributed Papers. Part 2.* https://www2.ioer.de/recherche/pdf/2001_blum_buildingpassport.pdf

Blum, A. (2001b). Die Basis-Konzeption Gebäudepass Schleswig- Holstein – Zielstellungen und Ansatz. In Arbeitsgemeinschaft Ökologischer Forschungsinstitute (Chair), *Umwelt, Gebäude und Gesundheit - von Energieeffizienz zur Raumlufthygiene,* Nürnberg.

Blum, A. (2002). „Building-Passport Schleswig-Holstein" – Supporting and Labelling Quality and Environmental Awareness in the Building Sector. In T. Dyrstad Petterson (Ed.), *Sustainable Building 2002 - 3rd international Conference on Sustainable Building.* EcoBuild. https://www.irbnet.de/daten/iconda/CIB2324.pdf

Blum, A. (2009). Documentation, Assessment and Labelling of Building Quality: The German 'Building Passport' Issue. In R. Vreeker & S. R. Curwell (Eds.), *Sustainable urban development series: Vol. 3. Sustainable urban development* (pp. 156–173). Routledge.

Bodenbender, M., & Kurzrock, B.-M. (2015). Success Factors for a Life Cycle Building Documentation. *RICS COBRA AUBEA*.

Böhms, M., van der Ende, M., Flickenschild, M., Borst, T., Raes, N., Cai, A., Gankema, Y., & Schinkel, R. (2023). *DBL Semantic Data Model: Providing standard form and meaning to digital building logbook data*. European Commission.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, *114*, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Bonduel, M., Pauwels, P., & Klein, R. (2022). Property modeling in the AECO industry. In P. Pauwels & K. McGlinn (Eds.), *Buildings and semantics: Data models and web technologies for the built environment* (pp. 26–49). CRC Press/Balkema.

Bone-Winkel, S., Focke, C., & Schulte, K.-W. (2016). Begriff und Besonderheiten der Immobilie als Wirtschaftsgut. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed.). De Gruyter Oldenbourg.

Bone-Winkel, S., Isenhöfer, B., Hofmann, P., & Franz, M. (2016). Projektentwicklung. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 173–248). De Gruyter Oldenbourg.

Borrmann, A., Beetz, J., Koch, C., Liebich, T., & Muhic, S. (2018). Industry Foundation Classes: A Standardized Data Model for the Vendor-Neutral Exchange of Digital Building Models. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling* (pp. 81–126). Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_5

Borrmann, A., König, M., Koch, C., & Beetz, J. (Eds.). (2018a). *Building Information Modeling*. Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018b). Building Information Modeling: Why? What? How? In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling* (pp. 1–24). Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_1

Borrmann, A., Schlenger, J., Bus, N., & Sacks, R. (2024). Aec Digital Twin Data - Why Structure Matters. In S. Skatulla & H. Beushausen (Eds.), *Lecture Notes in Civil Engineering: Vol. 357. Advances in Information Technology in Civil and Building Engineering: Proceedings of ICCCBE 2022 - Volume 1* (1st ed. 2024, pp. 651–669). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-031-35399-4_46

Both, P. von, Koch, V., & Kindsvater, A. (2013). *BIM - Potentiale, Hemmnisse und Handlungsplan: Analyse der Potentiale und Hemmnisse bei der Umsetzung der integrierten Planungsmethodik Building Information Modeling - BIM - in der deutschen Baubranche und Ableitung eines Handlungsplanes zur Verbesserung der Wettbewerbssituation*. *Forschungsinitiative ZukunftBau F: Vol. 2844*. Fraunhofer-IRB-Verl.

Brauer, K.-U. (2019a). Einführung in die Immobilienwirtschaft. In K.-U. Brauer (Ed.), *Grundlagen der Immobilienwirtschaft* (pp. 1–52). Springer Fachmedien Wiesbaden.

Brauer, K.-U. (Ed.). (2019b). *Grundlagen der Immobilienwirtschaft*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-21682-5

Brick Consortium. (2023, October 26). *Introduction — Brick Ontology Documentation*. https://docs.brickschema.org/intro.html

Brinkhoff, T., & Kresse, W. (2022). Databases. In W. Kresse & D. Danko (Eds.), *Springer handbooks. Springer Handbook of Geographic Information* (pp. 53–93). Springer International Publishing. https://doi.org/10.1007/978-3-030-53125-6_3

Buchholz, M. (2022). *Nachhaltigkeitsaspekte im Immobilienmanagement: Grundlagen und Möglichkeiten eines indikatorgestützten Ziel- und Berichtssystems* [Masterarbeit]. Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000143074

Buchholz, M., & Lützkendorf, T. (2022a). Building passports and material inventories – concepts, trends, job sharing. *IOP Conference Series: Earth and Environmental Science*, *1122*(1), 12038. https://doi.org/10.1088/1755-1315/1122/1/012038

Buchholz, M., & Lützkendorf, T. (2022b). Sustainability aspects in real estate management – basics and opportunities for an indicator-based target and reporting system in real estate companies. *Acta Polytechnica CTU Proceedings*, *38*, 11–17. https://doi.org/10.14311/APP.2022.38.0011

Buchholz, M., & Lützkendorf, T. (2023). European building passports: developments, challenges and future roles. *Buildings and Cities*, *4*(1), 902–919. https://doi.org/10.5334/bc.355

Buchholz, M., & Lützkendorf, T. (2024). Building passports in their role as building information systems - background, framework, implications. *IOP Conference Series: Earth and Environmental Science*, *1363*(1). https://doi.org/10.1088/1755-1315/1363/1/012107

Buildchain. (2024, December 22). *BUILDing knowledge book in the blockCHAIN distributed ledger*. https://buildchain-project.eu/

Building Passport. (2023). *The home of accurate building information*. https://www.buildingpassport.com/

Bundesamt für Bauwesen und Raumordnung. (2008). *Dokumentationsrichtlinie des BBR*. https://social.bscw.bund.de/pub/bscw.cgi/d5565541/DRL%202008-02_Gesamt.pdf

Bundesamt für Statistik. (2022). *Merkmalskatalog: Eidgenössisches Gebäude- und Wohnungsregister.*

Bundesamt für Wirtschaft und Ausfuhrkontrolle. (2024). *Energieberatung für Wohngebäude: Merkblatt für die Erstellung des individuellen Sanierungsfahrplans (iSFP)*. https://www.bafa.de/SharedDocs/Downloads/DE/Energie/ebw_merkblatt_isfp_2023.pdf?__blob=publicationFile&v=4

Bundesministerium des Innern, für Bau und Heimat, & Bundesministerium der Verteidigung. (2018). *Baufachliche Richtlinien Recycling: Arbeitshilfen zum Umgang mit Bau- und Abbruchabfällen sowie zum Einsatz von Recycling-Baustoffen auf Liegenschaften des Bundes.*

Bundesministerium des Innern, für Bau und Heimat, & Bundesministerium der Verteidigung. (2021). *Baufachliche Richtlinien Gebäudebestandsdokumentation: Vorgaben für die Gebäudebestandsdokumentation auf Liegenschaften des Bundes* (3rd ed.).

Bundesministerium für Verkehr, Bau und Stadtentwicklung, & Bundesamt für Bauwesen und Raumordnung. (2008). *Fortsetzung des Dialogs Bauqualität: Erarbeitung von Lehrmodulen zum Nachhaltigen Bauen zur Unterstützung der Aus- und Weiterbildung der am Bau Beteiligten.*

Bundesministerium für Verkehr, Bau- und Wohnungswesen. (2004). *Hausakte: Für den Neubau von Einfamilienhäusern*. MBVBW. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/ministerien/bmvbs/kostenguenstig-qualitaetsbewusst-bauen/downloads/Hausakte.pdf

Busen, T., Knechtel, M., Knobling, C., Nagel, E., Schuller, M., & Todt, B. (2017). *Bauaufnahme*. mediaTUM - Dokumenten- und Publikationsserver der Technischen Universität München. https://doi.org/10.14459/2016md1353273

Bushong, V., Abdelfattah, A. S., Maruf, A. A., Das, D., Lehman, A., Jaroszewski, E., Coffey, M., Cerny, T., Frajtak, K., Tisnovsky, P., & Bures, M. (2021). On Microservice Analysis and Architecture Evolution: A Systematic Mapping Study. *APPLIED SCIENCES-BASEL*, *11*(17), 7856. https://doi.org/10.3390/app11177856

Cajias, M., & Käsbauer, M. (2016). Kirchliches Immobilienmanagement. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 871–890). De Gruyter Oldenbourg.

Camunda. (2025, April 5). *Modeler*. https://camunda.com/de/platform/modeler/

CAPSA. (2024, August 12). *Der digitale Gebäudepass für fundierte Entscheidungen*. https://capsa-building.com/?lang=de

Carbonari, G., Ricci, M., Dourlens-Quaranta, S., Calderoni, M., Loureiro, T., Sterling, R., Glicker, J., Toth, Z [Zsolt], Volt, J., Groote, M. de, Borragán, G., Paduart, A., & Regel, S. de. (2020). *Building Logbook State of Play: Report 2of the Study on the Development of a European Union Framework for Buildings' Digital Logbook*. European Commission.

Carnet-numerique.co. (2023, April 28). *carnet numérique du logement*. https://carnet-numerique.co/

Celik, Y., Petri, I., & Rezgui, Y. (2023). Integrating BIM and Blockchain across construction lifecycle and supply chains. *Computers in Industry*, *148*, 103886. https://doi.org/10.1016/j.compind.2023.103886

*The Central Register of Buildings and Dwellings (BBR).* (2025, February 5). https://ncrr.au.dk/danish-registers/the-central-register-of-buildings-and-dwellings-bbr

Ceric, A., & Ivic, I. (2021). Network analysis of interconnections between theoretical concepts associated with principal–agent theory concerning construction projects. *Organization, Technology and Management in Construction: An International Journal*, *13*(2), 2450–2464. https://doi.org/10.2478/otmcj-2021-0025

Cetin, S. (2024). *The rise of sustainable building ordinances: Benchmarking, audits and retro-commissioning, and building performance standards*. https://www.gresb.com/nl-en/the-rise-of-sustainable-building-ordinances-benchmarking-audits-and-retro-commissioning-and-building-performance-standards/#

Chamari, L., Pauwels, P., & Petrova, E. (2022). Study of data needs and requirements in smart buildings. https://research.tue.nl/en/publications/study-of-data-needs-and-requirements-in-smart-buildings

Chowdhary, K. R. (2020). *Fundamentals of artificial intelligence*. Springer.

Christensen, G. (2011). The Building and Housing Register. *Scandinavian Journal of Public Health*, *39*(7), 106–108. https://doi.org/10.1177/1403494811399168

Chronicle. (2022). *About the project*. https://www.chronicle-project.eu/about/

Ciclica, & Green Building Council España. (2023, April 3). *PAS-E. Pasaporte del edificio*. http://pas-e.es/#/

Comiskey, D., McKane, M., Jaffrey, A., Wilson, P., & Mordue, S. (2017). An analysis of data sharing platforms in multidisciplinary education. *Architectural Engineering and Design Management*, *13*(4), 244–261. https://doi.org/10.1080/17452007.2017.1306483

Costin, A., Oullette, J. W., & Beetz, J. (2022). Building product models, terminologies, and object type libraries. In P. Pauwels & K. McGlinn (Eds.), *Buildings and semantics: Data models and web technologies for the built environment* (pp. 3–24). CRC Press/Balkema.

Cote, C. (2021, October 19). *4 Types of Data Analytics to Improve Decision-Making.* Harvard Business School. https://online.hbs.edu/blog/post/types-of-data-analysis

Dalla Valle, A., Campioli, A., & Lavagna, M. (2020). Life Cycle BIM-Oriented Data Collection: A Framework for Supporting Practitioners. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Springer eBook Collection. Digital Transformation of the Design, Construction and Management Processes of the Built Environment* (pp. 49–59). Springer International Publishing.

*Datamodel.* (2025, February 5). https://datafordeler.dk/grunddatamodel/

Decker, G., Freund, J., Lübbe, A., Mendling, J., Puhlmann, F., Schreiter, T., & Weidlich, M. (2010). *BPMN 2.0 Poster.* Conferences on Business Process Management. https://bpm-conference.org/BPMNPoster/

Dejaco, M. C., Moretti, N., & Re Cecconi, F. (2017). Streamlined management of the built environment: The district and the building logbook as risk prevention tools. In Maggioli Editore SpA (Ed.), *Re-shaping the construction industry* (pp. 185–194). ITA; Santarcangelo di Romagna; Maggioli Editore SpA. https://re.public.polimi.it/handle/11311/1032396

Dejaco, M. C., Re Cecconi, F., Moretti, N., Mannino, A., & Maltese, S. (2020). Building and District Data Organization to Improve Facility and Property Management. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Springer eBook Collection. Digital Transformation of the Design, Construction and Management Processes of the Built Environment* (pp. 255–265). Springer International Publishing.

Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*, 58–83. https://doi.org/10.36680/J.ITCON.2021.005

Deplace, F., Lützkendorf, T., & Mörmann, K. (2016). *Factsheets regarding Types of Investors and Stakeholders: RentalCal Deliverable Nr. 4.2*. IWU Institut Wohnen und Umwelt.

Di Biccari, C., Mangialardi, G., Lazoi, M., & Corallo, A. (2018). *Configuration Views from PLM to Building Lifecycle Management*. *IFIP Advances in Information and Communication Technology: Vol. 540.* https://doi.org/10.1007/978-3-030-01614-2_7

Di Giuda, G. M., Locatelli, M., Schievano, M., Pellegrini, L., Pattini, G., Giana, P. E., & Seghezzi, E. (2020). Natural Language Processing for Information and Project Management. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Springer eBook Collection. Digital Transformation of the Design, Construction and Management Processes of the Built Environment* (pp. 95–102). Springer International Publishing. https://doi.org/10.1007/978-3-030-33570-0_9

Diederichs, C. J. (2005). *Immobilienmanagement im Lebenszyklus: Projektentwicklung, Projektmanagement, Facility Management, Immobilienbewertung* (2., erw. und aktual. Aufl.). Springer.

Digibuild. (2022). *Overview - Digibuild*. https://digibuild-project.eu/project-overview/

Digital Building Passport. (2023). *What is Digital Building Passport all about?* https://passport.stepwise.pl/

DIN 18299:2023-09. *German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV):* General rules applying to all types of construction work.

DIN 276:2018-12. *Building costs*.

DIN 277:2021-08. *Areas and volumes in building construction*.

DIN 31051:2019-06. *Fundamentals of maintenance*.

DIN 32736:2000-08. *Building Management:* Definitions and scopes of services.

DIN 32835-1:2007-01. *Technical product documentation – Facility management documentation – Part 1: Concepts and methodology*.

DIN 32835-2:2007-01. *Technical product documentation – Facility management documentation – Part 2: Building occupancy documentation*.

DIN 69901-5:2009-01. *Project management – Project management systems – Part 5: Concepts*.

DIN EN 13306:2018-02. *Maintenance – Maintenance terminology:* Trilingual version.

DIN EN 15643:2021-12. *Sustainability of construction works – Framework for assessment of buildings and civil engineering works*.

DIN EN 15804:2020-03. *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*.

DIN EN 15941:2024-10. *Sustainability of construction works – Data quality for environmental assessment of products and construction works*.

DIN EN 15978:2024-05. *Sustainability of construction works – Assessment of environmental performance of buildings – Methology:* Draft.

DIN EN 16309:2014-12. *Sustainability of construction works – Assessment of social performance of buildings – Calculation methodology*.

DIN EN 16310:2013-05. *Engineering services:* Terminology to describe engineering services for buildings, infrastructure and industrial.

DIN EN 16627:2015-09. *Sustainability of construction works – Assessment of economic performance of buildings – Calculation methods*.

DIN EN 17412-1:2021-06. *Building Information Modelling – Level of Information Need – Part 1: Concepts and principles*.

DIN EN 17549-2:2023-09. *Building information modelling – Information structure based on EN ISO 16739-1 to exchange data templates and data sheets for construction objects – Part 2: Configurable construction objects and requirements*.

DIN EN 17632-1:2023-04. *Building Information Modelling (BIM) – Semantic modelling and linking (SML) – Part 1: Generic modelling patterns*.

DIN EN ISO /IEC 27001:2017-06. *Information technology – Security techniques – Information security management systems – Requirements*.

DIN EN ISO /IEC 27002:2024-01. *Information security, cybersecurity and privacy protection – Information security controls*.

DIN EN ISO 12006-2:2020-07. *Building construction – Organization of information about construction works – Part 2: Framework for classification*.

DIN EN ISO 16739-1:2021-11. *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data schema*.

DIN EN ISO 19650-1. *Organization and digitization of information about buildings and civil engineering works, including building information modelling - Information management using building information modelling - Part 1: Concepts and principles*.

DIN EN ISO 21597-1:2021-07. *Information container for linked document delivery – Exchange specificaton – Part 1: Container*.

DIN EN ISO 29481-1:2025-01 (draft). *Building information models – Information delivery manual – Part 1: Methodology and format*.

DIN EN ISO 41001:2018-09. *Facility management – Management systems – Requirements with guidance for use*.

DIN EN ISO/IEC 27000:2020-06. *Information technology – Security techniques – Information security management systems – Overview and vocabulary*.

DIN Fachbericht 151:2007-01. *Technical product documentation – Facility management documentation – Building documentation*.

DIN ISO 15226:2017-03. *Technical product documentation – Life cycle model and allocation of documents*.

DIN SPEC 91391-1:2019-04. *Common Data Environments (CDE) for BIM projects – Function sets and open data exchange between platforms of different vendors – Part 1: Components and function sets of a CDE; with digital attachment*.

DIN SPEC 91462:2022-02. *Requirements for the services of property management companies*.

DIN SPEC 91475:2024-03. *ESG – Data Point Initiative for the ecological analysis of Real Estate Stock; with digital attachment*.

Ditfurth, J. von, Linzmaier, T., Lohmann, M., & Terhalle, T. (2021). *Ecosystems in der Immobilienwirtschaft*. https://zia-deutschland.de/wp-content/uploads/2021/04/Deloitte-Zia-Studie_ECO-System1.pdf

Domdouzis, K., Lake, P., & Crowther, P. (2021). *Concise Guide to Databases*. Springer International Publishing. https://doi.org/10.1007/978-3-030-42224-0

Donath, D. (2008). *Bauaufnahme und Planung im Bestand: Grundlagen - Verfahren - Darstellung - Beispiele*. *Praxis*. Vieweg + Teubner.

dos Santos Gonçalves, J., Mateus, R., Dinis Silvestre, J., Pereira Roders, A., & Bragança, L. (2022). Building passport for the sustainable conservation of built heritage. *Journal of Cultural Heritage Management and Sustainable Development.* Advance online publication. https://doi.org/10.1108/JCHMSD-10-2021-0177

dos Santos Gonçalves, J., Mateus, R., Silvestre, J. D., & Roders, A. R. P. (2021). Beyond Good Intentions: The Role of the Building Passport for the Sustainable Conservation of Built Heritage to Behavioural Change. *Sustainability (Switzerland)*, *13*(15), 8280. https://doi.org/10.3390/su13158280

Dourlens-Quaranta, S., Carbonari, G., Groote, M. de, Borragán, G., Regel, S. de, Toth, Z [Zsolt], Volt, J., & Glicker, J. (2020). *Study on the Development of a European Union Framework for Digital Building Logbooks: Final Report*. European Commission. https://op.europa.eu/en/publication-detail/-/publication/40f40235-509e-11eb-b59f-01aa75ed71a1/language-en/format-PDF/source-184010877

Eckert, C. (2018). *IT-Sicherheit: Konzepte - Verfahren - Protokolle* (10. Auflage). *De Gruyter Studium*. De Gruyter. https://doi.org/10.1515/9783110563900

e-ehitus. (2025). *visioon - e-ehitus*. https://eehitus.ee/vision/

Eichstädt, J. (1982). Modernisation rationalisée des usines. *Batiment International, Building Research and Practice*, *10*(3), 177–181. https://doi.org/10.1080/09613218208551081

El Mokhtari, K., Panushev, I., & McArthur, J. J. (2022). Development of a Cognitive Digital Twin for Building Management and Operations. *Frontiers in Built Environment*, *8*, Article 856873. https://doi.org/10.3389/fbuil.2022.856873

Energistyrelsen. (2014). *Energirenovering med BedreBolig*. https://old.sparenergi.dk/forbruger/vaerktoejer/bedrebolig

Engelmann, F., & Großmann, C. (2021). Was wissen wir über Information? In K. Hildebrand, M. Gebauer, & M. Mielke (Eds.), *Daten- und Informationsqualität* (pp. 3–22). Springer Fachmedien Wiesbaden.

Enseling, A., Lützkendorf, T., & Buchholz, M. (2023). *Methodenkonvention Wirtschaftlichkeitsrechnung: Teil A: Hintergrundbericht*. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR).

Enshassi, M. A., Al Hallaq, K. A., & Tayeh, B. A. (2019). Limitation Factors of Building Information Modeling (BIM) Implementation. *The Open Construction & Building Technology Journal*, *13*(1), 189–196. https://doi.org/10.2174/1874836801913010189

Espinoza-Zambrano, P., Marmolejo-Duarte, C., & García-Hooghuis, A. (2023). Libro del Edificio Electrónico (LdE-e): Advancing towards a Comprehensive Tool for the Management and Renovation of Multifamily Buildings in Spain. *Sustainability (Switzerland)*, *15*(4), 2957. https://doi.org/10.3390/su15042957

Estonian Centre of Registers and Information Systems. (2021). *e-Land Register*. https://www.rik.ee/en/e-land-register

European Commission. (2017). *New European interoperability framework: Promoting seamless services and data flows for European public administrations*. https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf

European Commission. (2018). *Richtlinie (EU) 2018/844 des Europäischen Parlaments und des Rates vom 30. Mai 2018 zur Änderung der Richtlinie 2010/31/EU über die Gesamtenergieeffizienz von Gebäuden und der Richtlinie 2012/27/EU über Energieeffizienz (Text von Bedeutung für den EWR)*. https://eur-lex.europa.eu/legal-content/DE/TXT/?uri=CELEX%3A32018L0844

Regulation (EU) 2019/2088 of the European Parliament and of the Council of 27 November 2019 on sustainability-related disclosures in the financial services sector (Text with EEA relevance) (2019). https://eur-lex.europa.eu/eli/reg/2019/2088/oj

European Commission. (2019, April 5). *About Building Passport Flanders (Woningpas)*. https://joinup.ec.europa.eu/collection/egovernment/solution/building-passport-flanders-woningpas/about

Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance) (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852

European Commission. (2020). *Study on the development of a European Union framework for digital building logbooks: Executive Summary*. https://op.europa.eu/en/publication-detail/-/publication/9756617c-40de-11eb-b27b-01aa75ed71a1/language-en

Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R2139

European Commission. (2021). *Level(s): Putting circularity into practice*. https://environment.ec.europa.eu/document/download/896f7645-b978-4ace-8def-dd49ff7af801_en

Commission Delegated Regulation (EU) 2022/1288 of 6 April 2022 supplementing Regulation (EU) 2019/2088 of the European Parliament and of the Council (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R1288

Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (Text with EEA relevance) (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022L2464

European Commission. (2022). *Mapping relevant databases for the development of DBLs: Findings from the analysis of databses in three EU Member States - Estonia, France and Italy.*

COMMISSION DELEGATED DIRECTIVE (EU) …/ amending Directive 2013/34/EU of the European Parliament and of the Council as regards the adjustments of the size criteria for micro, small, medium-sized and large undertakings or groups, 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AC%282023%297020

Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council (2023). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R2486

European Commission. (2023). *Technical guidelines for digital building logbooks: Guidelines to the Member States on setting up and operationalising digital building logbooks under a common EU framework*. Draft.
Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (2024). https://eur-lex.europa.eu/eli/reg/2024/1781/oj
European Commission. (2025, February 26). *Commission simplifies rules on sustainability and EU investments* [Press release]. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_614
European Parliament and Council of the European Union. (2024). *DIRECTIVE (EU) 2024/1275 on the energy performance of buildings*. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401275
Council Directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency, Official Journal of the European Communities 28 (1993).
Fabbri, M. (2017). Understanding building renovation passports: customised solutions to boost deep renovation and increase comfort in a decarbonised Europe. *ECEEE Summer Study Proceedings*, 1409–1417.
Fabbri, M., Groote, M. de, & Rapf, O. (2016). *Building Renovation Passports: Customised roadmaps towards deep renovation and better homes*. Buildings Performance Institute Europe (BPIE). http://bpie.eu/wp-content/uploads/2017/01/Building-Passport-Report_2nd-edition.pdf
DIN EN ISO 41011:2019-04. *Facility Management – Begriffe (ISO 41011:2017)*.
Falkenberg, E. D., Hesse, W., Lindgreen, P., Nilsson, B. E., Oei, J. L. H., Rolland, C., Stamper, R. K., van Assche, F. J. M., Verrijn-Stuart, A. A., & Voss, K. (1998). *A framework of information system concepts: The FRISCO report (Web edition)*. University of Leiden, Department of Computer Science.
Farghaly, K., Soman, R. K., & Zhou, S. A. (2023). The evolution of ontology in AEC: A two-decade synthesis, application domains, and future directions. *Journal of Industrial Information Integration*, *36*, 100519. https://doi.org/10.1016/j.jii.2023.100519
Farshidi, S., Kwantes, I. B., & Jansen, S. (2023). Business process modeling language selection for research modelers. *Software and Systems Modeling.* Advance online publication. https://doi.org/10.1007/s10270-023-01110-8
Honorarordnung für Architekten und Ingenieure, 2013. https://www.gesetze-im-internet.de/hoai_2013/
Federal Statistical Office. (2023, May 30). *Federal Register of Buildings and Dwellings*. https://www.bfs.admin.ch/bfs/en/home/registers/federal-register-buildings-dwellings.html
Feldmann, P., Gerstner, N., Hofmann, P., Isenhäfer, B., Segerer, M., & Väth, A. (2016). Immobilienanalyse. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 363–424). De Gruyter Oldenbourg.
Fielt, E. (2013). Conceptualising business models: Definitions, frameworks and classifications.: Inaugural issue. *Journal of Business Models*, *1*(1). https://doi.org/10.5278/OJS.JBM.V1I1.707
Fransson, W., & Nelson, D. (2000). Management information systems for corporate real estate. *Journal of Corporate Real Estate*, *2*(2), 154–169. https://doi.org/10.1108/14630010010811284
Frei, M., Deb, C., Stadler, R., Nagy, Z., & Schlueter, A. (2020). Wireless sensor network for estimating building performance. *Automation in Construction*, *111*, 103043. https://doi.org/10.1016/j.autcon.2019.103043
Frické, M. (2009). The knowledge pyramid: a critique of the DIKW hierarchy. *Journal of Information Science*, *35*(2), 131–142. https://doi.org/10.1177/0165551508094050
Fuerst, F., & Dalton, B. (2019). Gibt es einen wissenschaftlichen Konsens zur Wirtschaftlichkeit nachhaltiger Immobilien? *Zeitschrift für Immobilienökonomie*, *5*(1-2), 173–191. https://doi.org/10.1365/s41056-019-00041-0
Gabriel, R. (2016). *Informationssystem*. https://www.enzyklopaedie-der-wirtschaftsinformatik.de/wi-enzyklopaedie/lexikon/uebergreifendes/Kontext-und-Grundlagen/Informationssystem/index.html
Gadatsch, A. (2020). *Grundkurs Geschäftsprozess-Management*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-27812-0
Ganter, M., & Lützkendorf, T. (2019). Information management throughout the life cycle of buildings – Basics and new approaches such as blockchain. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 12110. https://doi.org/10.1088/1755-1315/323/1/012110
Garcia-Teruel, R. M. (2020). Legal challenges and opportunities of blockchain technology in the real estate sector. *Journal of Property, Planning and Environmental Law*, *12*(2), 129–145. https://doi.org/10.1108/JPPEL-07-2019-0039

Gebäudeforum Klimaneutral. (2025a). *Individueller Sanierungsfahrplan*. https://www.gebaeudeforum.de/realisieren/isfp/

Gebäudeforum Klimaneutral. (2025b, March 19). *Nachhaltigkeitszertifizierungen*. https://www.gebaeudeforum.de/wissen/nachhaltiges-bauen-und-sanieren/zertifikate/

Gebretsadik, K. K. (2020). Challenges and Opportunity of UML Diagram for Software Project development as a complete Modeling Tool. *Journal of Mobile Computing & Application*, *7*(3), 46–48.

Geomer. (2025, April 5). *Gebäudedaten: fullHAUSde alle Gebäude Deutschlands: geomer GmbH*. https://www.geomer.de/geodaten-dienste/fullhausde.html

German Parliament. (1998). *Abschlußbericht der Enquete-Kommission „Schutz des Menschen und der Umwelt -Ziele und Rahmenbedingungen einer nachhaltig zukunftsverträglichen Entwicklung"*. https://dserver.bundestag.de/btd/13/112/1311200.pdf

German Sustainable Building Council. (2023a). *Gebäuderessourcenpass Bestand: Vollständige Fassung*. https://www.dgnb.de/de/nachhaltiges-bauen/zirkulaeres-bauen/gebaeuderessourcenpass

German Sustainable Building Council. (2023b, June 22). *Der Gebäuderessourcenpass der DGNB*. https://www.dgnb.de/de/themen/gebaeuderessourcenpass/index.php

Gernler, M. von. (2023). *Glossar zur Systematischen Literaturrecherche*. https://www.ub.unibe.ch/unibe/portal/unibiblio/content/e6250/e6264/e984201/e1237678/e1237679/pane1237693/e1237707/e1377201/Glossar_ger.pdf

Gessmann, R. (2008). *Ein internetbasiertes Gebäudedatenrepositorium als lebenszyklusorientierte Integrationsplattform* [Dissertation], Karlsruhe. https://doi.org/10.5445/KSP/1000009553

Glatte, T. (2014). *Entwicklung Betrieblicher Immobilien: Beschaffung und Verwertung Von Immobilien Im Corporate Real Estate Management*. *Leitfaden des Baubetriebs und der Bauwirtschaft Ser*. Springer Fachmedien Wiesbaden GmbH.

Glatte, T. (2021). *Corporate Real Estate Management*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-32222-9

Global Reporting Initiative. (2024, November 23). *Mission & history*. https://www.globalreporting.org/about-gri/mission-history/

Gluchowski, P., Gabriel, R., & Dittmar, C. (2008). *Management Support Systeme und Business Intelligence* (2nd ed.). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-68269-1

Godager, B., Onstein, E., & Huang, L. (2021). The Concept of Enterprise BIM: Current Research Practice and Future Trends. *IEEE Access*, *9*, 42265–42290. https://doi.org/10.1109/ACCESS.2021.3065116

Gómez-Gil, M., Espinosa-Fernández, A., & López-Mesa, B. (2022). Contribution of New Digital Technologies to the Digital Building Logbook. *Buildings*, *12*(12), 2129. https://doi.org/10.3390/buildings12122129

Gómez-Gil, M., Espinosa-Fernández, A., & López-Mesa, B. (2024). A new functionality for the digital building logbook: Assessing the progress of decarbonisation of national building sectors. *Environmental Impact Assessment Review*, *105*, 107393. https://doi.org/10.1016/j.eiar.2023.107393

Gómez-Gil, M., López-Mesa, B., & Espinosa-Fernández, A. (2022). European Digital Building Logbook: definition of its functionalities to maximize its potential. *EESAP13 International Conference 2022, 5-6 October Donostia-San Sebastián: Akten Liburua = Libro De Actas = Proceedings Book*, 63–71. https://addi.ehu.es/bitstream/handle/10810/59228/uaqpd224998.pdf?sequence=1#page=63

Gómez-Gil, M., Sesana, M. M., Salvalai, G., Espinosa-Fernández, A., & López-Mesa, B. (2023). The Digital Building Logbook as a gateway linked to existing national data sources: The cases of Spain and Italy. *Journal of Building Engineering*, *63*, 105461. https://doi.org/10.1016/j.jobe.2022.105461

Gonçalves, J. D. S., Lam, W. C., & Ritzen, M. (2024). The Role of Digital Building Logbooks for a Circular Built Environment. In C. de Wolf, S. Çetin, & N. M. P. Bocken (Eds.), *Circular Economy and Sustainability. A Circular Built Environment in the Digital Age* (1st ed. 2024, pp. 229–243). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-031-39675-5_13

Gondring, H. (2013). *Immobilienwirtschaft: Handbuch für Studium und Praxis* (3rd ed.). Franz Vahlen.

Gordon, M., Zimmerman, L. von, Haradhun, O., Campanella, D., Bräutigam, M., & Wolf, C. de. (2024). Digitising Building Materials for Reuse with Reality Capture and Scan-to-BIM Technologies. In C. de Wolf, S. Çetin, & N. M. P. Bocken (Eds.), *Circular Economy and Sustainability. A Circular Built Environment in the Digital Age* (1st ed. 2024, pp. 41–55). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-031-39675-5_3

Göswein, V., Carvalho, S., Cerqueira, C., & Lorena, A. (Eds.) (2022). *Circular material passports for buildings – Providing a robust methodology for promoting circular buildings*. : Vol. *1122*.

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., & Chowdhury, T. (2022). *Digital Product Passport: the ticket to achieving a climate neutral and circular European economy?* https://circulareconomy.europa.eu/platform/sites/default/files/cisl_digital_products_passport_report_v6.pdf

Graux, H. (2024). What is data ownership, and does it still matter under EU data law? An exploration of traditional concepts of data ownership, and of the expected impact of the Data Act. Advance online publication. https://doi.org/10.2830/052185

Green Finance Institute. (2021a). *Building Renovation Passports: Creating the Pathway to Zero Carbon Homes*. https://www.greenfinanceinstitute.co.uk/wp-content/uploads/2021/03/GREEN-FINANCE-BUILDING-RENOVATION-final.pdf

Green Finance Institute. (2021b). *Building Renovation Plans: An Information Requirements Framework*. https://legacy.greenfinanceinstitute.com/wp-content/uploads/2021/10/GFI-BUILDING-RENOVATION-PLANS-1.pdf

GRESB Real Estate. (2025). *Real Estate Standard and Reference Guide*. https://documents.gresb.com/generated_files/real_estate/2025/real_estate/reference_guide/complete.html

*Grunddataordbog.* (2024, November 4). https://grunddatamodel.datafordeler.dk/grunddataordbog/index.html

Gründerplattform. (2025, March 18). *Business Model Canvas: Dein ganzes Unternehmen auf einer Seite*. https://gruenderplattform.de/geschaeftsmodell/business-model-canvas-beispiele

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, *19*(8), 988–999. https://doi.org/10.1016/j.autcon.2010.09.002

Guerra-Santin, O., & Tweed, C. A. (2015). In-use monitoring of buildings: An overview of data collection methods. *Energy and Buildings*, *93*, 189–207. https://doi.org/10.1016/j.enbuild.2015.02.042

Gyuris, P., Khoja, A., Bazzan, E., Borgaro, P., Moro, A., Erber, S., Müller, J., Pál, B., Galai Dol, L., Lennon, B., & Malinovec Puček, M. (2023). *European Building Sustainability performance and energy certification Hub: D2.4 − The digital logbook, definition of data requirements, sources, and collection process*. https://eubsuperhub.eu/assets/content/Deliverables/D2.3.pdf

Hajdukiewicz, M., Byrne, D., Keane, M. M., & Goggins, J. (2015). Real-time monitoring framework to investigate the environmental and structural performance of buildings. *Building and Environment*, *86*, 1–16. https://doi.org/10.1016/j.buildenv.2014.12.012

Haneke, U., Trahasch, S., Zimmer, M., & Felden, C. (Eds.). (2021). *Data Science: Grundlagen, Architekturen und Anwendungen* (2., überarbeitete und erweiterte Auflage). dpunkt.verlag.

Hansen, H. R., Mendling, J., & Neumann, G. (2019). *Wirtschaftsinformatik: Grundlagen und Anwendungen* (12. völlig neu bearbeitete Auflage). *De Gruyter Studium*. De Gruyter. https://doi.org/10.1515/9783110608731

Hartenberger, U., & Lorenz, D. (2017). *Global Trends in Data Capture and Management in Real Estate and Construction*. https://www.rics.org/content/dam/ricsglobal/documents/to-be-sorted/global-trends-in-data-capture-and-management-in-real-estate-and-construction-rics.pdf

Hartenberger, U., Lorenz, D., & Lützkendorf, T. (2008). *Breaking the Vicious Circle of Blame - Making the Business Case for Sustainable Buildings.* https://doi.org/10.5445/IR/1000038462

Hartenberger, U., Ostermeyer, Y., & Lützkendorf, T. (2021). *The Building Passport: A tool for capturing and managing whole life data and information in construcion and real estate. Pracitcal guideline*. Global Alliance for Buildings and Construction. https://globalabc.org/sites/default/files/2021-09/GABC_The-Building-Passport_FINAL.pdf

Haus & Grund. (2023). *Wohnen in Zahlen: Ausgabe 2022/2023*. https://www.hausundgrund.de/sites/default/files/downloads/haus-grund-wohnen-zahlen.pdf

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International Journal of Project Management*, *35*(4), 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001

Heinrich, L. J., Heinzl, A., & Riedl, R. (2011). *Wirtschaftsinformatik: Einführung und Grundlegung* (4th ed. 2011). *Springer eBook Collection*. Springer Berlin Heidelberg; Imprint Springer. https://doi.org/10.1007/978-3-642-15426-3

Heinrich, M., & Lang, W. (2019). *Materials Passports - Best Practice Innovative Solutions for a Transition to a Circular Economy in the Built Environment*. Technische Universität München.

Helfrich, O.-D. (2021). Aufnahme einer Immobilie. In *Erfolgsstrategien für Immobilienmakler* (pp. 43–72). Springer Gabler, Wiesbaden. https://doi.org/10.1007/978-3-658-35683-5_4

Hellenborn, B., Eliasson, O., Yitmen, I., & Sadri, H. (2024). Asset information requirements for blockchain-based digital twins: A data-driven predictive analytics perspective. *Smart and Sustainable Built Environment*, *13*(1), 22–41. https://doi.org/10.1108/SASBE-08-2022-0183

Hellerforth, M. (2012). *BWL für die Immobilienwirtschaft* (2nd ed.). Oldenbourg Wissenschaftsverlag.

Hemmerling, M., & Bähre, B. (2020). *Informierte Architektur: Building Information Modeling für die Architekturpraxis*. De Gruyter. https://doi.org/10.1515/9783035619133

Hennig, B., Herz, S., Rawe, J., Bagherian, B., Enseling, A., Hinz, E., Böttcher, O., & Lammers, J. (2019). *Vorbildwirkung Bundesbau*. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR).

Hernández, J. L., Martín, S., Kapsalis, P., Katsigarakis, K., Sarmas, E., & Marinakis, V. (2023). Building a Data Lake for Smart Building Data: Architecture for Data Quality and Interoperability. In *14th International Conference on Information, Intelligence, Systems & Applications (IISA)* (pp. 1–8). IEEE. https://doi.org/10.1109/IISA59645.2023.10345892

Hicks, B. J. (2007). Lean information management: Understanding and eliminating waste. *International Journal of Information Management*, *27*(4), 233–249. https://doi.org/10.1016/j.ijinfomgt.2006.12.001

Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., Bensaali, F., & Amira, A. (2023). Ai-big data analytics for building automation and management systems: A survey, actual challenges and future perspectives. *Artificial Intelligence Review*, *56*(6), 4929–5021. https://doi.org/10.1007/s10462-022-10286-2

Hirschner, J., Hahr, H., & Kleinschrot, K. (2013). *Facility Management im Hochbau*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-01924-2

HMS. (2023, May 19). *Property registration | Fasteignaskrá*. https://fasteignaskra.is/english/properties/property-registration/

Hoitash, R., Hoitash, U., & Morris, L. (2021). eXtensible Business Reporting Language (XBRL): A Review and Implications for Future Research. *Auditing: A Journal of Practice & Theory*, *40*(2), 107–132. https://doi.org/10.2308/AJPT-2019-517

Holt, G. D. (2015). British construction business 1700-2000: proactive innovation or reactive evolution? *Construction Innovation*, *15*(3), 258–277. https://doi.org/10.1108/CI-02-2014-0016

HomeBook System. (2023, May 19). *Home - HomeBook System*. https://homebooksystem.fr/

Hong, S.-H., Lee, S.-K., & Yu, J.-H. (2019). Automated management of green building material information using web crawling and ontology. *Automation in Construction*, *102*, 230–244. https://doi.org/10.1016/j.autcon.2019.01.015

Honic, M., Kovacic, I., & Rechberger, H. (2019a). Der BIM-basierte materielle Gebäudepass als Optimierungswerkzeug. *Bautechnik*, *96*(3), 219–228. https://doi.org/10.1002/bate.201800089

Honic, M., Kovacic, I., & Rechberger, H. (Eds.) (2019b). *Concept for a BIM-based Material Passport for buildings*. : Vol. *225*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85063391625&doi=10.1088%2f1755-1315%2f225%2f1%2f012073&partnerID=40&md5=6706e8a9120cf5203c8a36f0ec7a3554

Hosamo, H. H., Imran, A., Cardenas-Cartagena, J., Svennevig, P. R., Svidt, K., & Nielsen, H. K. (2022). A Review of the Digital Twin Technology in the AEC-FM Industry. *Advances in Civil Engineering*, *2022*, 1–17. https://doi.org/10.1155/2022/2185170

House of Commons Library. (2010). *Home Information Packs: a short history: Research Paper 10/69*. https://researchbriefings.files.parliament.uk/documents/RP10-69/RP10-69.pdf

Howarth, T., & Greenwood, D. (2017). *Construction Quality Management: Principles and practice*. Routledge. https://www.taylorfrancis.com/books/9781317191407 https://doi.org/10.4324/9781315563657

Hu, V. (2018). *Attribute-Based Access Control*. *Artech House information security and privacy series*. Artech House.

Hunhevicz, J. J., & Hall, D. M. (2020). Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. *Advanced Engineering Informatics*, *45*, 101094. https://doi.org/10.1016/j.aei.2020.101094

Hypotheek.winkel. (2023, May 10). *De woningpas vertelt je alles over je huis*. https://www.hypotheekwinkel.be/huizenjacht/woningpas/

iECO. (2022, May 4). *Über das Projekt - ieco-gaiax*. https://ieco-gaiax.de/projekt/

Ilmastoviisaat taloyhtiöt. (2022, April 22). *Ilmastoviisaat Taloyhtiöt*. https://ilmastoviisaat.fi/

Inmon, W. H., Linstedt, D., & Levins, M. (2019). *Data architecture: A primer for the data scientist* (Second Edition). Academic Press.

International Association of Assessing Officers. (2018). *Standard on Automated Valuation Models (AVMs): A criterion for measuring fairness, quality, equity and accuracy*.

International Building Performance & Data Initiative. (2022a). *The global data model for real estate*. https://ibpdi.org/
International Building Performance & Data Initiative. (2022b). *JSON Physical Model*. https://ibpdi.org/wp-content/uploads/2022/08/IBPDI_Real_Estate_CDM_V2.0_documentation.html#contents
Irish Green Building Council. (2020). *Introducing Building Renovation Passports in Ireland*. https://www.igbc.ie/wp-content/uploads/2020/09/Introducing-BRP-In-Ireland-Feasibility-Study.pdf
ISO 15392:2019-12. *Sustainability in buildings and civil engineering works — General principles*.
ISO 16745-1:2017-05. *Sustainability in buildings and civil engineering works — Carbon metric of an existing building during use stage :* Calculation, reporting and communication.
ISO 21929-1:2011-11. *Sustainability in building construction — Sustainability indicators:* Framework for the development of indicators and a core set of indicators for buildings.
ISO 21931-1:2022-06. *Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment :* Buildings.
ISO/DIS 19005-4:2024-12 (draft). *Document management — Electronic document file format for long-term preservation :* Part 4: Use of ISO 32000-2 (PDF/A-4).
ISO/IEC TS 38505-3:2021-12. *Information technology — Governance of data:* Guidelines for data classification.
Jacobsen, A., Miranda Azevedo, R. de, Juty, N., Batista, D., Coles, S., Cornet, R., Courtot, M., Crosas, M., Dumontier, M., Evelo, C. T., Goble, C., Guizzardi, G., Hansen, K. K., Hasnain, A., Hettne, K., Heringa, J., Hooft, R. W., Imming, M., Jeffery, K. G., . . . Schultes, E. (2020). FAIR Principles: Interpretations and Implementation Considerations. *Data Intelligence*, *2*(1-2), 10–29. https://doi.org/10.1162/dint_r_00024
Jäger, A. (2021). *Der Einfluss nachhaltigkeitsbezogener Objektmerkmale auf den Wert von Immobilien – ein Beitrag zur Weiterentwicklung von Datenhaltung und Wertermittlungsverfahren*. *Karlsruher Schriften zur Bau-, Wohnungs- und Immobilienwirtschaft: Vol. 10*. KIT Scientific Publishing. https://doi.org/10.5445/KSP/1000130842
Jang, K., Kim, J.-W., Ju, K.-B., & An, Y.-K. (2021). Infrastructure BIM Platform for Lifecycle Management. *Applied Sciences (Switzerland)*, *11*(21), 10310. https://doi.org/10.3390/app112110310
Jaskula, K., Kifokeris, D., Papadonikolaki, E., & Rovas, D. (2022). Common Data Environments in construction: State-of-the-art and challenges for practical implementation. *SSRN Electronic Journal.* Advance online publication. https://doi.org/10.2139/ssrn.4249458
Jedelsky, A. (2022). Anwendungsfälle für Blockchain in der Immobilienwirtschaft. In C. Jacob & S. Kukovec (Eds.), *Auf dem Weg zu einer nachhaltigen, effizienten und profitablen Wertschöpfung von Gebäuden* (pp. 473–484). Springer Fachmedien Wiesbaden.
Jones, P. (2006). *Building log book toolkit : a guide and templates for preparing building log books*. CIBSE.
Just, T., & Stapenhorst, H. (2018). *Real Estate Due Diligence*. Springer International Publishing. https://doi.org/10.1007/978-3-319-62510-2
Jylhä, T., & Suvanto, M. E. (2015). Impacts of poor quality of information in the facility management field. *Facilities*, *33*(5/6), 302–319. https://doi.org/10.1108/F-07-2013-0057
Kämpf-Dern, A. (2009). Immobilienwirtschaftliche Managementebenen und -aufgaben.: Definitions- und Leistungskatalog des Immobilienmanagements. *Arbeitspapiere Zur Immobilienwirtschaftlichen Forschung Und Praxis*(15).
Kämpf-Dern, A., & Pfnür, A. (2009). Grundkonzept des Immobilienmanagements: Ein Vorschlag zur Strukturierung immobilienwirtschaftlicher Managementaufgaben. *Arbeitspapiere Zur Immobilienwirtschaftlichen Forschung Und Praxis*(14).
Kappes, M. (2022). *Netzwerk- und Datensicherheit: Eine praktische Einführung* (3rd ed. 2022). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-16127-9
Karagiannis, D., Mayr, H. C., & Mylopoulos, J. (Eds.). (2016). *Domain-Specific Conceptual Modeling: Concepts, Methods and Tools*. Springer International Publishing. https://doi.org/10.1007/978-3-319-39417-6
Kassem, M., Kelly, G., Dawood, N., Serginson, M., & Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. *Built Environment Project and Asset Management*, *5*(3), 261–277. https://doi.org/10.1108/BEPAM-02-2014-0011
Katsifaraki, A., Malavazos, C., Tsalis, C., Toffanin, R., Olivadese, R., Ibba, A., D'Angelo, L., Alonso, R., Iousef, S., Andriopoulos, P., Shiel, P., Klumbytė, E., Gómez Meirás, M., Mitsou Errandonea, M., Pérez Pardo, N., Polychroniadis, P., Tsarchopoulos, P., Larsen, A., Capdevila, S., . . . Byrne, N. (2024). *Building Performance Digitalisation and Dynamic Logbooks for Future Value-Driven Services: Deliverable 2.1*

*CHRONICLE Business requirements, Use cases & System architecture*. https://www.chronicle-project.eu/wp-content/uploads/2024/08/D2.1-CHRONICLE-Business-requirements-Use-cases-System-architecture.pdf

Kaufmann, M., & Meier, A. (2023). *SQL- & NoSQL-Datenbanken* (9. Aufl.). Springer Berlin Heidelberg.

Kehrli, J. (2021). *Modern Information System Architectures*. https://www.niceideas.ch/roller2/badtrash/entry/modern-information-system-architectures

Kelly, J. G., Aouad, G., Rezgui, Y., & Crofts, J. (1997). Information systems developments in the UK construction industry. *Automation in Construction*, *6*(1), 17–22. https://doi.org/10.1016/S0926-5805(96)00175-6

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmstrom, J. (2019). Digital Twin: Vision, Benefits, Boundaries, and Creation for Buildings. *IEEE Access*, *7*, 147406–147419. https://doi.org/10.1109/ACCESS.2019.2946515

Khatri, V., & Brown, C. V. (2010). Designing data governance. *Communications of the ACM*, *53*(1), 148–152. https://doi.org/10.1145/1629175.1629210

Kiedrowski, M. *Fragebogen zur Gebäudeversicherung*. https://www.wohngebaeudeversicherung.eu/media/erfassungsbogen-wohngeb_ude-fairfekt_003_.pdf

Kis Papp, L. (1999). Aufnahme- und Erfassungstechniken Raumbezogener Daten zum Aufbau und zur Aktualisierung von Dreidimensionalen Gebäudeinformationssystemen. *Periodica Polytechnica Civil Engineering*, *43*(1), 29–41. https://pp.bme.hu/ci/article/view/663

Klinc, R., & Turk, Ž. (2019). Construction 4.0 – Digital Transformation of One of the Oldest Industries. *Economic and Business Review*, *21*(3). https://doi.org/10.15458/ebr.92

Knobloch, C. (2017). *Bauakten und Baupläne*. https://www.leo-bw.de/themenmodul/sudwestdeutsche-archivalienkunde/archivaliengattungen/akten/inhaltliche-unterscheidung/bauakten-und-bauplane

Knublauch, H., & Kontokostas, D. (2018, January 31). *Shapes Constraint Language (SHACL)*. https://www.w3.org/TR/shacl/#core-components-logical

Kontaxis, D., Tsoulos, G., Athanasiadou, G., & Giannakis, G. (2022). Wireless Sensor Networks for Building Information Modeling. *Telecom*, *3*(1), 118–134. https://doi.org/10.3390/telecom3010007

Koronen, C., Gokarakonda, S., Toth, Z [Zsolt], & Mauricio, C. (2024). *Unlocking the potential of digital building logbooks for a climate-neutral building stock*. https://demo-blog.eu/wp-content/uploads/2024/09/DemoBLog-policy-factsheet-WEBSept-2024-1.pdf

Kotu, V., & Deshpande, B. (2019). *Data Science: Concepts and practice* (2nd ed.). Elsevier. https://doi.org/10.1016/C2017-0-02113-4

KPMG. (2021). *The value of Information Management in the construction and infrastructure sector: A report commissioned by the University of Cambridge's Centre for Digital Built Britain (CDBB)*. https://www.cdbb.cam.ac.uk/files/cdbb_econ_value_of_im_report.pdf

Krause, A., Zimmermann, M., Herda, & Ingmar. (2022). *Überlegungen zu einem Gebäude- und Wohnungsregister: Aufbau, Pflege und Nutzung*. https://www.destatis.de/DE/Methoden/WISTA-Wirtschaft-und-Statistik/2022/04/ueberlegungen-gebaeude-wohnungsregister-042022.pdf?__blob=publicationFile

Krcmar, H. (1990). Bedeutung und Ziele von Informationssystem-Architekturen. *Wirtschaftsinformatik*, *32*(5), 395–402.

Krcmar, H. (2015). *Informationsmanagement* (6. edition). Springer Gabler.

Krieger, P., & Lausberg, C. (2021). Entscheidungen, Entscheidungsfindung und Entscheidungsunterstützung in der Immobilienwirtschaft: Eine systematische Literaturübersicht. *Zeitschrift Für Immobilienökonomie*, *7*(1), 1–33. https://doi.org/10.1365/s41056-020-00044-2

Krogstie, J. (2012). *Model-Based Development and Evolution of Information Systems: A Quality Approach*. Springer London Limited.

Kubler, S., Buda, A., Robert, J., Främling, K., & Le Traon, Y. (2016). Building Lifecycle Management System for Enhanced Closed Loop Collaboration. *International Conference on Product Lifecycle Management*, *492*, 423–432. https://doi.org/10.1007/978-3-319-54660-5_38

Kumar, S., Menezes, A., Giri, S., & Kotikela, S. (2024). What The Phish! Effects of AI on Phishing Attacks and Defense. *International Conference on AI Research*, *4*(1), 218–226. https://doi.org/10.34190/icair.4.1.3224

Kumar, V [Vimal], Chaisiri, S., & Ko, R. (2017). A data-centric view of cloud computing. In V. Kumar, S. Chaisiri, & R. Ko (Eds.), *IET security Series: Vol. 05. Data security in cloud computing* (pp. 1–17). Institution of Engineering & Technology.

Kumar, V [Vishal], & Teo, E. A. L. (2021). Perceived benefits and issues associated with COBie datasheet handling in the construction industry. *Facilities*, *39*(5/6), 321–349. https://doi.org/10.1108/F-09-2019-0100

Kurzrock, B.-M. (2017). Lebenszyklus von Immobilien. In N. B. Rottke & M. Thomas (Eds.), *Immobilienwirtschaftslehre - Management* (pp. 421–446). Springer Fachmedien Wiesbaden.

Kurzrock, B.-M., Bodenbender, M., & Müller, P. M. (2019). Von der analogen zur digitalen lebenszyklusübergreifenden Gebäudedokumentation. In M. Peyinghaus & R. Zeitner (Eds.), *Springer eBook Collection. Transformation Real Estate: Changeprozesse in Unternehmen und für Immobilien* (pp. 271–296). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-26244-0_17

Kurzrock, B.-M., Rothenbusch, J., Schütz, K., & Huang, F. (2023). *Maschinelles Lernen im Bereich Gebäudedokumentation*. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR).

Langs, G., Munro, K., & Wazir, R. (2022). Machine Learning. In S. Papp, W. Weidinger, K. Munro, B. Ortner, A. Cadonna, G. Langs, R. Licandro, M. Meir-Huber, D. Nikolić, Z. Toth, B. Vesela, R. Wazir, & G. Zauner (Eds.), *Hanser eLibrary. The Handbook of Data Science and AI: Generate value from data with machine learning and data analytics* (pp. 201–238). Carl Hanser Verlag GmbH & Co. KG.

Laudon, K. C., & Laudon, J. P. (2014). *Management information systems: Managing the digital firm*. Authorised adaptation from the United States edition (Thirteenth Edition). Prentice Hall.

Laux, H., Gillenkirch, R. M., & Schenk-Mathes, H. Y. (2014). *Entscheidungstheorie*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-55258-8

Leindecker, G., Askar, R., Güngör, B., Blázquez, T., Turbina, N., Gómez-Gil, M., Karanafti, A., Bragança, L., & Wolf, C. de (2025). Material and Building Passports as Supportive Tools for Enhancing Circularity in Buildings. *Springer Tracts in Civil Engineering*, *Part F3604*, 507–543. https://doi.org/10.1007/978-3-031-73490-8_18

Lennartsson, M., Yitmen, I., Movaffaghi, H., & Linderoth, H. (2020). Framework for Digital Development in Industrialized Housebuilding. In *Advances in Transdisciplinary Engineering*.

Leopoldsberger, G., Thomas, M., & Naubereit, P. (2016). Immobilienbewertung. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 425–480). De Gruyter Oldenbourg.

Libórîo, P., Fragoso, R., Sousa Monteiro, C., Fernandes, J., & Silva, E. (2018). *The logbook data quest: Setting up indicators and other requirements for a renovation passport*. https://ibroad-project.eu/downloads/REPORTD24

Licandro, R. (2022). Computer Vision. In S. Papp, W. Weidinger, K. Munro, B. Ortner, A. Cadonna, G. Langs, R. Licandro, M. Meir-Huber, D. Nikolić, Z. Toth, B. Vesela, R. Wazir, & G. Zauner (Eds.), *Hanser eLibrary. The Handbook of Data Science and AI: Generate value from data with machine learning and data analytics* (pp. 317–346). Carl Hanser Verlag GmbH & Co. KG.

Liferay DXP. (2023, May 18). *Publieke welkomspagina - Liferay DXP*. https://woningpas.vlaanderen.be/

Lill, I., & Witt, E. (2019). An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers. *Emerald Reach Proceedings Series*, *2*, 297–303. https://doi.org/10.1108/S2516-2853201902

Link, J. (2024). *How generative AI for architecture is transforming design*. https://www.autodesk.com/design-make/articles/generative-ai-for-architecture?utm_source=chatgpt.com

Lorenz, D., & Lützkendorf, T. (2008). Next Generation Decision Support Instruments for the Property Industry: Understanding the Financial Implications of Sustainable Building. In *Proceedings of the 2008 World Sustainable Building Conference: World SB08 Melbourne, Melbourne Convention Centre, 21 - 25 September 2008.* ASN Events.

Lorenz, D., & Lützkendorf, T. (2011). Sustainability and property valuation. *Journal of Property Investment & Finance*, *29*(6), 644–676. https://doi.org/10.1108/14635781111171797

Lu, Q., Xie, X., Heaton, J., Parlikad, A. K., & Schooling, J. (2020). From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management. *Studies in Computational Intelligence*, *853*, 392–404. https://doi.org/10.1007/978-3-030-27477-1_30

Luscuere, L. M. (2017). Materials Passports: Optimising value recovery from materials. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 25–28. https://doi.org/10.1680/jwarm.16.00016

Lützkendorf, T. (2000). *Beiträge zur Umsetzung von Prinzipien einer Nachhaltigen Entwicklung im Baubereich* [Habilitationsschrift]. Bauhaus-Universität Weimar.

Lützkendorf, T., & Lorenz, D. (2014). *Sustainability Metrics: Translation and Impact on Property Investment and Management* [UNEP FI Property Working Group report]. https://www.unepfi.org/fileadmin/documents/UNEPFI_SustainabilityMetrics_Web.pdf

Lützkendorf, T., & Speer, T. M. (2005). Alleviating asymmetric information in property markets: building performance and product quality as signals for consumers. *Building Research & Information*, *33*(2), 182–195. https://doi.org/10.1080/0961321042000323815

Magnet, D. (1989, October 3). Integrated security and building management system. In *Proceedings. International Carnahan Conference on Security Technology* (pp. 69–78). IEEE. https://doi.org/10.1109/CCST.1989.751956

Malagnino, A., Mangialardi, G., Zavarise, G., & Corallo, A. (2017). *From Traditional Construction Industry Process Management to Building Lifecycle Management*. *IFIP Advances in Information and Communication Technology: Vol. 517.* https://doi.org/10.1007/978-3-319-72905-3_30

Malinovec Puček, M., Khoja, A., Bazzan, E., & Gyuris, P. (2023a). A Data Structure for Digital Building Logbooks: Achieving Energy Efficiency, Sustainability, and Smartness in Buildings across the EU. *Buildings*, *13*(4), 1082. https://doi.org/10.3390/buildings13041082

Malinovec Puček, M., Khoja, A., Bazzan, E., & Gyuris, P. (2023b). A Data Structure for Digital Building Logbooks: Achieving Energy Efficiency, Sustainability, and Smartness in Buildings across the EU. *Buildings*, *13*(4). https://doi.org/10.3390/buildings13041082

Mangialardi, G., Di Biccari, C., Pascarelli, C., Lazoi, M., & Corallo, A. (2017). Bim and PLM Associations in Current Literature. In J. Ríos, A. Bernard, A. Bouras, & S. Foufou (Eds.), *Product Lifecycle Management and the Industry of the Future* (Vol. 517, pp. 345–357). Springer International Publishing. https://doi.org/10.1007/978-3-319-72905-3_31

Marsden, P. (2019). *Digital Quality Management in Construction*. CRC Press LLC.

Mashhadi, A., Kawsar, F., & Acer, U. G. (2014). Human Data Interaction in IoT: The ownership aspect. In *2014 IEEE World Forum on Internet of Things (WF-IoT)* (pp. 159–162). IEEE. https://doi.org/10.1109/WF-IoT.2014.6803139

Matarneh, S., Elghaish, F., Rahimian, F. P., Dawood, N., & Edwards, D. (2022). Automated and interconnected facility management system: An open IFC cloud-based BIM solution. *Automation in Construction*, *143*, 104569. https://doi.org/10.1016/j.autcon.2022.104569

May, M. (2018). Motivation. In M. May (Ed.), *CAFM-Handbuch* (pp. 1–4). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-21357-2_1

Mayer, H. (2018). Digitalization of legacy building data: Preparation of Printed Building Plans for the BIM Process. *Proceedings Ofthe 7th International Conference on Smart Cities and Green ICTSystems (SMARTGREENS 2018)*, 304–310. https://pdfs.semanticscholar.org/d19f/0463749072976f78db5f7cff28fcf0d63de3.pdf

Mêda, P., Fauth, J., Schranz, C., Sousa, H., & Urban, H. (2024). Twinning the path of digital building permits and digital building logbooks – Diagnosis and challenges. *Developments in the Built Environment*, *20.* https://doi.org/10.1016/j.dibe.2024.100573

Mêda Magalhães, P., Calvetti, D., Kifokeris, D., & Kassem, M. (2022). A process-based framework for digital building logbooks. In *Proceedings of the 2022 European Conference on Computing in Construction.* University of Turin. https://doi.org/10.35490/ec3.2022.183

Mehlis, J. (2005). *Analyse des Datenentstehungsprozesses und Entwicklung eines Entscheidungsmodells für eine wirtschaftliche Vorgehensweise bei der lebenszyklusorientierten Immobiliendatenerfassung und -pflege* [Dissertation]. Universität Leipzig.

Meins, E., Lützkendorf, T., Lorenz, D., Leopoldsberger, G., Frank, S. O. K., Burkhard, H.-P., Stoy, C., & Bienert, S. (2011). *Nachhaltigkeit und Wertermittlung von Immobilien, Leitfaden für Deutschland, Österreich und die Schweiz (NUWEL)*. CCRS. https://doi.org/10.5167/UZH-76697

Mell, P., & Grance, T. (2011). *The NIST definition of cloud computing: Recommendations of the National Institute of Standards and Technology*. https://nvlpubs.nist.gov/nistpubs/legacy/sp/nistspecialpublication800-145.pdf

Mertens, P. (2013). *Integrierte Informationsverarbeitung 1*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-8349-4395-8

Mertens, P., Bodendorf, F., König, W., Schumann, M., Hess, T., & Buxmann, P. (2017). *Grundzüge der Wirtschaftsinformatik*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-53362-8

Mezquita, Y., Parra-Domínguez, J., Pérez-Pons, M. E., Prieto, J., & Manuel Corchado, J. (2022). Blockchain-based land registry platforms: a survey on their implementation and potential challenges. *Logic Journal of the IGPL*, *30*(6), 1017–1027. https://doi.org/10.1093/jigpal/jzac010

Michigan tech. (2023). *Computer Science*. https://www.mtu.edu/cs/what/

Michl, P. (2018). *Hedonische Preisindizes für Transaktionen von Wohneigentum - dargestellt am Beispiel der Stadt Karlsruhe. Ein Beitrag zur Bereitstellung von Zeitreihen für die Marktwertermittlung und Marktprognose*. Dissertation. KIT Scientific Publishing. https://doi.org/10.5445/IR/1000082420

Miller, W., & Lützkendorf, T. (2016). Capturing sustainable housing characteristics through Electronic Building Files. In *Sustainable Built Environment Conference 2016 in Hamburg : Strategies, Stakeholders, Success factors, 7th - 11th March 2016 ; Conference Proceedings* (pp. 190–199).

Miller, W., Zedan, Sherif, & Kirsch, E. (2020). *Electronic building passport: The role of an Electronic Building Passport for energy efficiency compliance and quality assurance in residential buildings*. https://www.energymining.sa.gov.au/__data/assets/pdf_file/0009/820719/NEEBP-Electronic-Building-Passport-Public-Report.pdf

Miloslavskaya, N., & Tolstoy, A. (2016). Big Data, Fast Data and Data Lake Concepts. *Procedia Computer Science*, *88*, 300–305. https://doi.org/10.1016/j.procs.2016.07.439

Ministry of the Environment and Energy. (2021). *Electronic Building ID*. https://ypen.gov.gr/ilektroniki-taftotita-ktiriou-ypochreotiki-apo-01-02-2021/

Ministry of Transport, Building and Housing. (2001). *Guideline for Sustainable Building*. https://www.bbsr.bund.de/BBSR/EN/publications/ministries/BMVBS/SpecialPublication/1994_2006/DL_GuidelineSustainable.pdf

Moretti, N., Xie, X., Merino, J., Brazauskas, J., & Parlikad, A. K. (2020). An openBIM Approach to IoT Integration with Incomplete As-Built Data. *Applied Sciences (Switzerland)*, *10*(22), 8287. https://doi.org/10.3390/app10228287

Moselhi, O., Bardareh, H., & Zhu, Z. (2020). Automated Data Acquisition in Construction with Remote Sensing Technologies. *APPLIED SCIENCES-BASEL*, *10*(8), 2846. https://doi.org/10.3390/app10082846

Munaro, M. R., Fischer, A. C., Azevedo, N. C., & Tavares, S. F. (2019). Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 12018. https://doi.org/10.1088/1755-1315/225/1/012018

Murphy, G. D. (2009). Improving the quality of manually acquired data: Applying the theory of planned behaviour to data quality. *Reliability Engineering & System Safety*, *94*(12), 1881–1886. https://doi.org/10.1016/j.ress.2009.05.008

NaWoh. (2024). *Qualitätssiegel Nachhaltiger Wohnungsbau - Neubau - Steckbriefsatz NaWoh 4.0.* Verein zur Förderung der Nachhaltigkeit im Wohnungsbau e.V. https://www.nawoh.de/uploads/pdf/Steckbriefsatz_NaWoh_4.0-QNG_240905.pdf

Nebauer, C. (2012). *Immobilien-Controlling für institutionelle Investoren: Eine theoretische und empirische Untersuchung*. Dissertation. *Schriften zur Immobilienökonomie: Bd. 62*. Immobilien-Manager-Verl.

Nern, T. (2021). *Automatisierte Standortanalyse und Investitionsempfehlung anhand von mikrogeografischen Daten mittels künstlicher Intelligenz und Big Data*. https://snic.de/wp-content/uploads/2021/11/BidF_Automatisierte_Standortanalyse.pdf

NV-Versicherungen. *Antrag Wohngebäude*. https://www.nv-online.de/fileadmin/downloadcenter/wohngebaeude/2-0/Antrag_NV_Wohnhaus_2.0.pdf

Oberti, I., & Paoletti, I. (2020). Da.Ma.Tra: Material Traceability Database. In B. Daniotti, M. Gianinetto, & S. Della Torre (Eds.), *Springer eBook Collection. Digital Transformation of the Design, Construction and Management Processes of the Built Environment* (pp. 85–93). Springer International Publishing.

Olofsson, M., Holmgren, H., & Persson, K. (2024). Comparative analysis of traditional and modern measured survey methods. *International Journal of Surveying and Structural Engineering*, *5*(1), 14–19.

openDBL. (2024a, December 22). *Project Overview - Digital Building Logbook | openDBL*. https://www.opendbl.eu/project-overview

openDBL. (2024b, December 23). *Technical Ambition*. https://www.opendbl.eu/technical-ambition

OpenImmo. (2022). *What is OpenImmo ?* http://www.openimmo.de/go.php/p/33/cm_int_uk.htm#xml

Opić, M., Härtig, M., May, M., Schlundt, M., & Turianskyj, N. (2018). Anwendungsfelder für den IT-Einsatz im FM. In M. May (Ed.), *CAFM-Handbuch* (pp. 45–71). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-21357-2_4

Opoku, D.-G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*, 102726. https://doi.org/10.1016/j.jobe.2021.102726

Oraee, M., Hosseini, M. R., Papadonikolaki, E., Palliyaguru, R., & Arashpour, M. (2017). Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. *International Journal of Project Management*, *35*(7), 1288–1301. https://doi.org/10.1016/j.ijproman.2017.07.001

Osberghaus, T. (2008). *Abbruchplanung: Eine Handlungshilfe für Bauherren* (3., aktualisierte Aufl.). *Altlasten und Grundwasserschadensfälle*. Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg.

OSCRE International. (2022). *OSCRE Industry Data Model*. https://www.oscre.org/Industry-Data-Model/Introducing-the-Data-Model

Osmanoglu, T. E. (2014). *Identity and access management: Business performance through connected intelligence*. Syngress.

Oxlade, S. (2019, January 15). buildingSMART Data Dictionary - buildingSMART International. *BuildingSMART International*. https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., . . . Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ (Clinical Research Ed.)*, *372*, n71. https://doi.org/10.1136/bmj.n71

Panza, L., Bruno, G., & Lombardi, F. (2022). A Collaborative Architecture to support Circular Economy through Digital Material Passports and Internet of Materials. *IFAC-PapersOnLine*, *55*(10), 1491–1496. https://doi.org/10.1016/j.ifacol.2022.09.601

Papp, S., Weidinger, W., Munro, K., Ortner, B., Cadonna, A., Langs, G., Licandro, R., Meir-Huber, M., Nikolić, D., Toth, Z [Zoltan], Vesela, B., Wazir, R., & Zauner, G. (Eds.). (2022). *Hanser eLibrary*. *The Handbook of Data Science and AI: Generate value from data with machine learning and data analytics*. Carl Hanser Verlag GmbH & Co. KG. https://doi.org/10.3139/9781569908877

Parn, E. A., & Edwards, D. (2019). Cyber threats confronting the digital built environment. *Engineering, Construction and Architectural Management*, *26*(2), 245–266. https://doi.org/10.1108/ECAM-03-2018-0101

Pärn, E. A., Edwards, D. J., & Sing, M. (2017). The building information modelling trajectory in facilities management: A review. *Automation in Construction*, *75*, 45–55. https://doi.org/10.1016/j.autcon.2016.12.003

Paul, N. (2007). A Complex-Based Building Information System. In J. Kieferle & K. Ehlers (Eds.), *eCAADe proceedings, Proceedings of the 25th International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe)* (pp. 591–598). eCAADe. https://doi.org/10.52842/conf.ecaade.2007.591

Pauwels, P., Zhang, S., & Lee, Y.-C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, *73*, 145–165. https://doi.org/10.1016/j.autcon.2016.10.003

Peckham, J., & Maryanski, F. (1988). Semantic data models. *ACM Computing Surveys*, *20*(3), 153–189. https://doi.org/10.1145/62061.62062

Pedral Sampaio, R., Aguiar Costa, A., & Flores-Colen, I. (2022). A Systematic Review of Artificial Intelligence Applied to Facility Management in the Building Information Modeling Context and Future Research Directions. *Buildings*, *12*(11), 1939. https://doi.org/10.3390/buildings12111939

Pelzeter, A., & Trübestein, M. (2016). Real Estate Asset Management, Property Management und Facility Management. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 287–362). De Gruyter Oldenbourg.

Pereira, J. L., & Silva, D. (2016). Business Process Modeling Languages: A Comparative Framework. In Á. Rocha, A. M. Correia, H. Adeli, L. P. Reis, & M. Mendonça Teixeira (Eds.), *SpringerLink Bücher: Vol. 444. New Advances in Information Systems and Technologies* (Vol. 444, pp. 619–628). Springer International Publishing. https://doi.org/10.1007/978-3-319-31232-3_58

Perera, S., Nanayakkara, S., Rodrigo, M., Senaratne, S., & Weinand, R. (2020). Blockchain technology: Is it hype or real in the construction industry? *Journal of Industrial Information Integration*, *17*, 100125. https://doi.org/10.1016/j.jii.2020.100125

Petzold, F. (2001). *Computergestützte Bauaufnahme als Grundlage für die Planung im Bestand: Untersuchungen zur digitalen Erfassung und Modellbildung* [Dissertation]. Bauhaus-Universität Weimar.

Peyinghaus, M., Zeitner, R., & Kempter, A.-K. (2022). Megatrends und ihr Einfluss auf die Immobilienwirtschaft. In M. Peyinghaus, R. Zeitner, & A.-K. Kempter (Eds.), *Leading Real Estate: Führung von*

*Immobilienunternehmen unter Einfluss aktueller Megatrends* (pp. 1–29). Springer Fachmedien Wiesbaden; Imprint Springer Vieweg. https://doi.org/10.1007/978-3-658-39998-6_1
Pfnür, A. (2011). *Modernes Immobilienmanagement*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-79468-4
Pfnür, A., & Wagner, B. (2018). *Transformation der Immobilienwirtschaft: Eine empirische Studie deutscher immobilienwirtschaftlicher Akteure*. Technische Universität Darmstadt.
Picot, A., & Reichwald, R. (1990). Informationswirtschaft. In E. Heinen (Ed.), *Industriebetriebslehre* (pp. 241–394). Gabler Verlag.
Picot, A., Reichwald, R., Wigand, R. T., Möslein, K. M., Neuburger, R., & Neyer, A.-K. (2020). Die grenzenlose Unternehmung. Advance online publication. https://doi.org/10.1007/978-3-658-28565-4
Pidgeon, A., & Dawood, N. (2021). Bridging the gap between theory and practice for adopting meaningful collaborative BIM processes in infrastructure projects, utilising multi-criteria decision making (MCDM). *Journal of Information Technology in Construction*, *26*, 783–811. https://doi.org/10.36680/J.ITCON.2021.043
Pizarro, P. N., Hitschfeld, N., Sipiran, I., & Saavedra, J. M. (2022). Automatic floor plan analysis and recognition. *Automation in Construction*, *140*, 104348. https://doi.org/10.1016/j.autcon.2022.104348
Platform CB'23. (2022). *Guide for the Construction Sector Parts 1 + 2: Working agreements and substantiation for passports in a circular construction sector*. https://platformcb23.nl/images/downloads/2022/Guide-to-Passports-for-the-Construction-Sector_3.pdf
Plociennik, C., Pourjafarian, M., Nazeri, A., Windholz, W., Knetsch, S., Rickert, J., Ciroth, A., Precci Lopes, Alice do Carmo, Hagedorn, T., Vogelgesang, M., Benner, W., Gassmann, A., Bergweiler, S., Ruskowski, M., Schebek, L., & Weidenkaff, A. (2022). Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP*, *105*, 122–127. https://doi.org/10.1016/j.procir.2022.02.021
Plößl, F., & Just, T. (2020). *Megatrends in der Immobilienwirtschaft*. KPMG.
Pohl, A., & Vornholz, G. (2016). *Global Markets Real Estate: Megatrends und ihre Bedeutung für die Entwicklung von Immobilienmärkten.* Deutsche Hypo. https://www.deutsche-hypo.de/content/uploads/2016/09/Deutsche-Hypo_Global-Markets_Megatrends.pdf
Preethichandra, D. M. G., Suntharavadivel, T. G., Kalutara, P., Piyathilaka, L., & Izhar, U. (2023). Influence of Smart Sensors on Structural Health Monitoring Systems and Future Asset Management Practices. *Sensors*, *23*(19). https://doi.org/10.3390/s23198279
Preuß, N., & Schöne, L. B. (2016). *Real Estate und Facility Management*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-48291-9
PricewaterhouseCoopers. (2024, June 27). *Identity and Access Management (IAM) 2024 Trends and beyond*. https://www.pwc.be/en/news-publications/2024/iam-trends.html
Produktkollen. (2023, May 19). *Produktkollen - En loggbok för byggnader*. https://www.produktkollen.se/
Propach, V., Mrzigod, A., & Weidner, S. (2023). Der Gebäuderessourcenpass – ein Steuerungsinstrument für effektiven Ressourcenschutz im Massivbau. *Beton- Und Stahlbetonbau*, *118*(5), 353–360. https://doi.org/10.1002/best.202300024
Property Log Book. (2023). *Property Log Book*. https://propertylogbook.co.uk/
Qing, L., Tao, G., & Ping, W.-J. (2014). Study on Building Lifecycle Information Management Platform Based on BIM. *Research Journal of Applied Sciences, Engineering and Technology*, *7*(1), 1–8. https://doi.org/10.19026/rjaset.7.212
Rahm, E., Saake, G., & Sattler, K.-U. (2015). *Verteiltes und Paralleles Datenmanagement*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-45242-0
Raj, A., Sharma, S., Singh, J., & Singh, A. (2023). Revolutionizing Data Entry: An In-Depth Study of Optical Character Recognition Technology and Its Future Potential. *International Journal for Research in Applied Science and Engineering Technology*, *11*(2), 645–653. https://doi.org/10.22214/ijraset.2023.49108
Rampini, L., & Cecconi, F. R. (2022). Artificial intelligence in construction asset management: a review of present status, challenges and future opportunities. *Journal of Information Technology in Construction*, *27*, 884–913. https://doi.org/10.36680/j.itcon.2022.043
Rashdi, R., Martínez-Sánchez, J., Arias, P., & Qiu, Z. (2022). Scanning Technologies to Building Information Modelling: A Review. *Infrastructures*, *7*(4), 49. https://doi.org/10.3390/infrastructures7040049
Rasmussen, M. H., Pauwels, P., Lefrançois, M., & Schneider, G. F. (2021, June 28). *Building Topology Ontology*. https://w3c-lbd-cg.github.io/bot/

Real Estate Standards Organization. (2023, November 9). *Data Dictionary | RESO - Real Estate Standards Organization*. https://www.reso.org/data-dictionary/

RealEstateCore. (2023, November 9). *What is an ontology?* https://dev.realestatecore.io/docs/

Reisinger, H., Buschmann, H., Walter, B., Lixia, R., & Daxbeck, H. (2014). *Gebäudepass: Erarbeitung von Grundlagen für die Standardisierung von Gebäudepässen als Gebäudematerialinformationssystem*. Umweltbundesamt Österreich.

Reuver, M. de, Sørensen, C., & Basole, R. C. (2018). The Digital Platform: A Research Agenda. *JOURNAL of INFORMATION TECHNOLOGY*, *33*(2), 124–135. https://doi.org/10.1057/s41265-016-0033-3

Richardson, L., & Amundsen, M. (2013). *Restful web APIs*. O'Reilly.

Ridzuan, F., & Wan Zainon, W. M. N. (2019). A Review on Data Cleansing Methods for Big Data. *Procedia Computer Science*, *161*, 731–738. https://doi.org/10.1016/j.procs.2019.11.177

Rock, V., & Hennig, K. (2016). Immobilienmarketing. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 651–714). De Gruyter Oldenbourg.

Rock, V., & Seilheimer, S. (2024). Digitalisierung im Asset Management. In D. Piazolo (Ed.), *Immobilien Asset Management* (pp. 185–209). Springer Fachmedien Wiesbaden GmbH. https://doi.org/10.1007/978-3-658-40879-4_9

Rogage, K., & Greenwood, D. (2020). Data transfer between digital models of built assets and their operation & maintenance systems. *Journal of Information Technology in Construction*, *25*, 469–481. https://doi.org/10.36680/j.itcon.2020.027

Rohde, C., Lützkendorf, T., Schulz, M., Lorenz, D., Kertes, J., & Immendörfer, A. (2011). *Projekt objektINFO: Analyse der Informationsbedürfnisse ausgewählter Akteursgruppen zu Objektinformationen im Lebenszyklus von Gebäuden als Voraussetzung für die Entwicklung einer Bauwerks-Informations-Systematik (BIS). Forschungsinitiative Zukunft Bau*. Fraunhofer IRB Verlag.

Rohweder, J. P., Kasten, G., Malzahn, D., Piro, A., & Schmid, J. (2021). Informationsqualität – Definitionen, Dimensionen und Begriffe. In K. Hildebrand, M. Gebauer, & M. Mielke (Eds.), *Daten- und Informationsqualität* (pp. 23–43). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-30991-6_2

Ropohl, G. (2009). *Allgemeine Technologie: Eine Systemtheorie der Technik* (3rd ed.). Universitätsverlag Karlsruhe.

Rottke, N. B. (2017a). Immobilienarten. In N. B. Rottke & M. Thomas (Eds.), *Immobilienwirtschaftslehre - Management.* Springer Fachmedien Wiesbaden.

Rottke, N. B. (2017b). Immobilienrisikomanagement. In N. B. Rottke & M. Thomas (Eds.), *Immobilienwirtschaftslehre - Management* (pp. 961–990). Springer Fachmedien Wiesbaden.

Rottke, N. B. (2017c). Immobilienwirtschaftslehre als wissenschaftliche Disziplin. In N. B. Rottke & M. Thomas (Eds.), *Immobilienwirtschaftslehre - Management.* Springer Fachmedien Wiesbaden.

Royal Institution of Chartered Surveyors. (2018). *Environmental risks and global real estate*. https://www.rics.org/content/dam/ricsglobal/documents/standards/Environmental_risks_and_global_real_estate_1st_edition_GN_2018.pdf

Royal Institution of Chartered Surveyors. (2020). *Technical due diligence of commercial property: RICS guidance note, global*. Royal Institution of Chartered Surveyors (RICS).

Royal Institution of Chartered Surveyors. (2022a). *International Building Operation Standard: A framework for assessing building performance*. https://www.rics.org/content/dam/ricsglobal/documents/standards/IBOS_Practice%20Information.pdf

Royal Institution of Chartered Surveyors. (2022b). *RICS Data Standards*. https://www.rics.org/de/upholding-professional-standards/sector-standards/construction/rics-data-standards/

Rudolph, M. (2022). Digitale Open Data Grundstücks- und Potenzialanalysen mittels 2D-Geodaten und 3D-Stadtmodellen. In C. Jacob & S. Kukovec (Eds.), *Auf dem Weg zu einer nachhaltigen, effizienten und profitablen Wertschöpfung von Gebäuden* (pp. 123–136). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-34962-2_7

Runkler, T. A. (2020). *Data Analytics: Models and algorithms for intelligent data analysis* (Third edition). *Springer eBook Collection*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-29779-4

Saari, A., Junnila, S., & Vimpari, J. (2022). Blockchain's Grand Promise for the Real Estate Sector: A Systematic Review. *Applied Sciences*, *12*(23), 11940. https://doi.org/10.3390/app122311940

Sack, H. (2014). Linked Data Technologien – Ein Überblick. In T. Pellegrini (Ed.), *X-media-press. Linked Enterprise Data: Management und Bewirtschaftung vernetzter Unternehmensdaten mit Semantic-Web-Technologien* (pp. 21–62). Springer. https://doi.org/10.1007/978-3-642-30274-9_2

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *Bim Handbook: A guide to building information modeling for owners, managers, designers, engineers, contractors, and facility managers* (Third edition). John Wiley & Sons, Inc. https://doi.org/10.1002/9781119287568

Salminen, A. (2011). *Communicating with XML*. Springer.

Sawhney, A., & Odeh, I. S. (2020). Digital ecosystems in the construction industry: Current state and future trends. In A. Sawhney, M. Riley, J. Irizarry, & M. Riley (Eds.), *Construction 4.0* (pp. 42–61). Routledge.

Schaefer, W. F. (1993). Instruments for the management of knowledge. *Automation in Construction*, *2*(3), 187–198. https://doi.org/10.1016/0926-5805(93)90040-5

Schäfer, C. (2024). *PropTech Germany 2024 Studie*. https://proptechgermanystudie.de/wp-content/uploads/2024/12/PropTech-Germany-2024-Studie.pdf

Schäfer, H., Lützkendorf, T., Gromer, C., & Rohde, C. (2010). *ImmoWert: Integration von Nachhaltigkeitsaspekten in die Wertermittlung und Risikobeurteilung von Einzelimmobilien und Gebäudebeständen ; [Abschlussbericht zum Projekt ; ein Gemeinschaftsprojekt der Partner: Universität Stuttgart, Karlsruher Institut für Technologie KIT (ehem. Universität Karlsruhe), LBBW-Immobilien. Forschungsinitiative ZukunftBau: F 2753*. Fraunhofer IRB Verl.

Schäfers, W., Ecke, C., Högner, J., & Dietzel, M. (2016). Öffentliches Immobilienmanagement. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 837–870). De Gruyter Oldenbourg.

Schäfers, W., Gier, S., & Dietzel, M. (2016). Betriebliches Immobilienmanagement. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 785–836). De Gruyter Oldenbourg.

Schapke, S.-E., Beetz, J., König, M., Koch, C., & Borrmann, A. (2018). Collaborative Data Management. In A. Borrmann, M. König, C. Koch, & J. Beetz (Eds.), *Building Information Modeling* (pp. 251–277). Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_14

Scheer, A.-W. (1991). *Architektur integrierter Informationssysteme: Grundlagen der Unternehmensmodellierung*. Springer.

Scheer, A.-W. (1998). *Wirtschaftsinformatik: Referenzmodelle für industrielle Geschäftsprozesse* (7th ed.). Springer.

Scheer, A.-W. (2001). *ARIS - Modellierungsmethoden, Metamodelle, Anwendungen* (4. Aufl.). Springer. http://digitale-objekte.hbz-nrw.de/webclient/DeliveryManager?pid=1461333&custom_att_2=simple_viewer

Scherenberg, F. von, Hellmeier, M., & Otto, B. (2024). Data Sovereignty in Information Systems. *Electronic Markets*, *34*(1). https://doi.org/10.1007/s12525-024-00693-4

Schiller, G., Lehmann, I., Gruhler, K., Hennersdorf, J., Lützkendorf, T., Mörmann, K., Knappe, F., Muchow, N., & Reinhardt, J. (2022). *Kartierung des anthropogenen Lagers IV: Eerarbeitung eines Gebäudepass- und Gebäudekatasterkonzepts zur regionalisierten Erfassung des Materialhaushaltes mit dem Ziel der Optimierung des Recyclings*. Umweltbundesamt.

Schlachter, M. (2019). *Einfluss von Objekt- und Standorteigenschaften auf den Wert von Wohnimmobilien* [Dissertation]. Technische Universität München. https://mediatum.ub.tum.de/1488250

Schulte, K.-W., Bone-Winkel, S., & Schäfers, W. (Eds.). (2016). *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed.). De Gruyter Oldenbourg.

Schulte, K.-W., Sotelo, R., Allendorf, G. J., Ropeter-Ahlers, S.-E., & Lang, S. (2016). Immobilieninvestition. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 579–650). De Gruyter Oldenbourg.

Schütte, R. (1998). *Grundsätze ordnungsmäßiger Referenzmodellierung* [Dissertation]. Universität Münster.

Scotish government. (2020, August 12). *Home Report*. https://www.mygov.scot/buying-a-home/home-report

Seaton, H., Savian, C., Sepasgozar, S., & Sawhney, A. (2022). *Digital twins from design to handover of constructed assets*. Royal Institution of Chartered Surveyors (RICS).

Seduikyte, L., Morsink-Georgali, P.-Z., Panteli, C., Chatzipanagiotidou, P., Stavros, K., Ioannidis, D., Stasiulienė, L., Spūdys, P., Pupeikis, D., Jurelionis, A., & Fokaides, P. (2022). *Next-Generation Energy Performance Certificates. What novel implementation do we need?* Zenodo. https://doi.org/10.5281/zenodo.8189221

Sesana, M. M., & Salvalai, G. (2018). A review on Building Renovation Passport: Potentialities and barriers on current initiatives. *Energy and Buildings*, *173*, 195–205. https://doi.org/10.1016/j.enbuild.2018.05.027

Sesana, M. M., Salvalai, G., Brutti, D., Mandin, C., & Wei, W. (2021). ALDREN: A Methodological Framework to Support Decision-Making and Investments in Deep Energy Renovation of Non-Residential Buildings. *Buildings*, *11*(1), 3. https://doi.org/10.3390/buildings11010003

Shafer, S. M., Smith, H. J., & Linder, J. C. (2005). The power of business models. *Business Horizons*, *48*(3), 199–207. https://doi.org/10.1016/j.bushor.2004.10.014

Siccardi, S., & Villa, V. (2023). Trends in Adopting BIM, IoT and DT for Facility Management: A Scientometric Analysis and Keyword Co-Occurrence Network Review. *Buildings*, *13*(1), 15. https://doi.org/10.3390/buildings13010015

Signorini, M., Spagnolo, S. L., & Dejaco, M. C. (2021). A Digital Logbook as an Interactive Tool to Fulfil Service Companies' Needs and Requirements in Building Renovations. *IOP Conference Series: Materials Science and Engineering*, *1044*(1), 12010. https://doi.org/10.1088/1757-899X/1044/1/012010

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Society of Property Researchers. (2021). *Guideline of Real Estate Data Exchange (gif-IDA): Version 3.0.*

Soibelman, L., Wu, J., Caldas, C., Brilakis, I., & Lin, K.-Y. (2008). Management and analysis of unstructured construction data types. *Advanced Engineering Informatics*, *22*(1), 15–27. https://doi.org/10.1016/j.aei.2007.08.011

Sousa Monteiro, C., Fragoso, R., Papaglastra, M., Deliyannis, A., Pehnt, M., Mellwig, P., Lempik, J., & Werle, M. (2018). *The Concept of iBRoad: the Individual Building Renovation Roadmap and building logbook: Potential functionalities and graphical guidelines when setting up the iBRoad concept*. https://ibroad-project.eu/downloads/REPORTD35

Söylemez, M., Tekinerdogan, B., & Kolukısa Tarhan, A. (2022). Challenges and Solution Directions of Microservice Architectures: A Systematic Literature Review. *APPLIED SCIENCES-BASEL*, *12*(11), 5507. https://doi.org/10.3390/app12115507

Sozialdemokratische Partei Deutschlands, BÜNDNIS 90/DIE GRÜNEN, & Freie Demokratische Partei. (2022). *Mehr Fortschritt wagen: Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit* [Koalitionsvertrag 2021-2025]. https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag/Koalitionsvertrag_2021-2025.pdf

Stachowiak, H. (1973). *Allgemein Modelltheorie*. Springer.

Starzner, S., Wurmer-Weiss, P., Graubner, C.-A., Schneider, C., Renner, A., Lützkendorf, T., & Zak, J. (2007). *Formulierung von Anforderungen an die Datenbereitstellung nach Art, Qualität und Aggregationsstufe: Netzwerk Lebenszyklusdaten - Arbeitskreis Nutzersichten im Baubereich*. Forschungszentrum Karlsruhe, Institut für Technikfolgenabschätzung und Systemanalyse.

Statistisches Bundesamt. (2008). *Klassifikation der Wirtschaftszweige 2008 (WZ 2008)*. Statistisches Bundesamt.

Steinmüller, W. (1993). *Informationstechnologie und Gesellschaft: Einführung in die Angewandte Informatik*. Wiss. Buchges.

Strahringer, S. (1998). Ein sprachbasierter Metamodellbegriff und seine Verallgemeinerung durch das Konzept des Metaisierungsprinzips. *CEUR Workshop Proceedings Zur Modellierung '98*, *9*.

Strategyzer. (2025, March 17). *Business Model Canvas*. https://www.strategyzer.com/library/the-business-model-canvas

Su, T., Li, H., & An, Y. (2021). A BIM and machine learning integration framework for automated property valuation. *Journal of Building Engineering*, *44*, 102636. https://doi.org/10.1016/j.jobe.2021.102636

Sunyaev, A. (2020). *Internet Computing*. Springer International Publishing. https://doi.org/10.1007/978-3-030-34957-8

Tagg, A. (2018). *Technical Due Diligence and Building Surveying for Commercial Property*. Routledge.

Talamo, C., & Bonanomi, M. (2015). *Knowledge Management and Information Tools for Building Maintenance and Facility Management*. Springer International Publishing. https://doi.org/10.1007/978-3-319-23959-0

Tavakoli, P., Yitmen, I., Sadri, H., & Taheri, A. (2024). Blockchain-based digital twin data provenance for predictive asset management in building facilities. *Smart and Sustainable Built Environment*, *13*(1), 4–21. https://doi.org/10.1108/SASBE-07-2023-0169

Teece, D. J. (2010). Business Models, Business Strategy and Innovation. *Long Range Planning*, *43*(2-3), 172–194. https://doi.org/10.1016/j.lrp.2009.07.003

Teichmann, S. A. (2009). *Integriertes Facilities Management in Europa: Theoretische Konzeption, empirische Untersuchung und Marktanalyse zur Gestaltung und Steuerung von Wertschöpfungspartnerschaften im internationalen Kontext*. Dissertation. *Schriften zur Immobilienökonomie: Bd. 55*. Immobilien Manager Verl.

Terai, T., & Kaneko, Y. (1990). Information — Open coding system. *Batiment International, Building Research and Practice*, *18*(3), 169–173. https://doi.org/10.1080/01823329008727035

Tilmes, R., Jakob, R., & Pitschke, C. (2016). Privates Immobilienmanagement. In K.-W. Schulte, S. Bone-Winkel, & W. Schäfers (Eds.), *Immobilienökonomie I: Betriebswirtschaftliche Grundlagen* (5.th ed., pp. 891–918). De Gruyter Oldenbourg.

Tomaszuk, D., & Haudebourg, T. (2025, February 24). *RDF 1.2 Schema: W3C Working Draft*. https://www.w3.org/TR/rdf12-schema/

Toth, Z [Zsolt], Volt, J., Zuhaib, S., & Broer, T. (2021). *Introductary Reports: Building Logbook*. https://x-tendo.eu/toolboxes/building-logbook/

Treleaven, P., Barnett, J., Knight, A., & Serrano, W. (2021). Real Estate Data Marketplace. *AI and Ethics*, *1*(4), 445–462. https://doi.org/10.1007/s43681-021-00053-4

Turianskyj, N., Bender, T., Kalweit, T., Koch, S., May, M., & Opić, M. (2018). Datenerfassung und Datenmanagement im FM. In M. May (Ed.), *CAFM-Handbuch* (pp. 229–272). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-21357-2_9

Turk, Ž., & Klinc, R. (2017). Potentials of Blockchain Technology for Construction Management. *Procedia Engineering*, *196*, 638–645. https://doi.org/10.1016/j.proeng.2017.08.052

Tuscher, M., Hanak, M., Navratilova, V., Ticha, A., Goncalves Martinho R.F., & Cruz da Cunha M.M. (2024). Usage of Building Passports and BIM in Multi-Criteria Evaluation. *Procedia Computer Science*, *239*. https://doi.org/10.1016/j.procs.2024.06.273

United Kingdom Government. (2002). *Building Regulations: Part L.*

Urschel, O. (2010). *Risikomanagement in der Immobilienwirtschaft : ein Beitrag zur Verbesserung der Risikoanalyse und -bewertung*. Dissertation. *Karlsruher Schriften zur Bau-, Wohnungs- und Immobilienwirtschaft: Vol. 4*. KIT Scientific Publishing. https://doi.org/10.5445/KSP/1000016517

van Capelleveen, G., Vegter, D., Olthaar, M., & van Hillegersberg, J. (2023). The anatomy of a passport for the circular economy: a conceptual definition, vision and structured literature review. *Resources, Conservation & Recycling Advances*, *17*, 200131. https://doi.org/10.1016/j.rcradv.2023.200131

Vanlande, R., Nicolle, C., & Cruz, C. (2008). IFC and building lifecycle management. *Automation in Construction*, *18*(1), 70–78. https://doi.org/10.1016/j.autcon.2008.05.001

Varoudis, T., & Patlakas, P. (2014). A Model for a Distributed Building Information System. In E. M. Thompson (Ed.), *eCAADe proceedings, Proceedings of the 32nd International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe) [Volume 2]* (pp. 505–513). eCAADe. https://doi.org/10.52842/conf.ecaade.2014.2.505

VDI 6026:2015-04 part 1.1. *Documentation in the building services Contents and format of planning, execution and review documents to satisfy the needs of the FM:* Requirements to be met by the documentation.

VDI 6039:2011-06. *Facility management - Managing of building commissioning:* Methods and procedures for building-services installations.

VDI 6041:2017-07. *Facility Management - Technical monitoring of buildings and building services*.

VDI 6070 Part 1. *Room book:* General requirements and fundamentals.

VDI 6210:2024-10 part 1. *Demolition of structural and technical facilities:* Draft.

VDI-MT 3810 Part 1:2023-03. *Operation and maintenance of buildings and building installations:* Fundamentals.

Verordnung über die Grundsätze für die Ermittlung der Verkehrswerte von Immobilien und der für die Wertermittlung erforderlichen Daten (Immobilienwertermittlungsverordnung), 2021. https://www.gesetze-im-internet.de/immowertv_2022/BJNR280500021.html

Vesela, B. (2022). Data Visualization. In S. Papp, W. Weidinger, K. Munro, B. Ortner, A. Cadonna, G. Langs, R. Licandro, M. Meir-Huber, D. Nikolić, Z. Toth, B. Vesela, R. Wazir, & G. Zauner (Eds.), *Hanser eLibrary. The Handbook of Data Science and AI: Generate value from data with machine learning and data analytics* (pp. 385–410). Carl Hanser Verlag GmbH & Co. KG.

Virta, M., Hovorka, F., & Lippo, A. (2012). *Building passport as a tool to evaluate sustainability of building*. https://santruptieng.files.wordpress.com/2015/05/building-passport-as-a-tool-to-evaluate-sustainability-of-building_a10.pdf

Vlaanderen. (2023, May 18). *Postinterventiedossier (PID)*. https://www.vlaanderen.be/postinterventiedossier-pid

VÖB-Kommission für Bewertungsfragen. (2006). *VÖB-ImmobilienAnalyse – Instrument zur Beurteilung des Chance- / Risikoprofils von Immobilien.* Bundesverband Öffentlicher Banken Deutschlands. https://www.voeb-service.de/fileadmin/user_upload/Fachpublikation_VOEB-Immobilienanalyse_September_2006.pdf

Voigtländer, M., Henger, R. M., Haas, H., Schier, M., Just, T., Bienert, S., Geiger, P., Hesse, M., Braun, N., Schäfer, P., Jaroszek, L., Kröncke, T.-A., & Steiniger, B. (2013). *Gesamtwirtschaftliche Bedeutung der Immobilienwirtschaft*. Deutscher Verband für Wohnungswesen, Städtebau und Raumordnung e.V. (DV) und Gesellschaft für Immobilienwirtschaftliche Forschung e.V. (gif).

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Volt, J., Toth, Z [Zsolt], Glicker, J., Groote, M. de, Borragán, G., Regel, S. de, Dourlens-Quaranta, S., & Carbonari, G. (2020). *Definition Of The Digital Building Logbook: Report 1 of the Study on the Development of a European Union Framework for Buildings' Digital Logbook*. European Commission. https://op.europa.eu/en/publication-detail/-/publication/cacf9ee6-06ba-11eb-a511-01aa75ed71a1/language-en

vom Brocke, J. (2015). *Referenzmodellierung: Gestaltung und Verteilung von Konstruktionsprozessen*. Dissertation (2nd ed.). *Advances in information systems and management science: Vol. 4*. Logos-Verl.

Weigel, N. (2021). Datenqualitätsmanagement – Steigerung der Datenqualität mit Methode. In K. Hildebrand, M. Gebauer, & M. Mielke (Eds.), *Daten- und Informationsqualität* (pp. 67–85). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-30991-6_4

Weinhardt, C., Anandasivam, A., Blau, B., Borissov, N., Meinl, T., Michalk, W., & Stößer, J. (2009). Cloud Computing – A Classification, Business Models, and Research Directions. *Business & Information Systems Engineering*, *1*(5), 391–399. https://doi.org/10.1007/s12599-009-0071-2

Wendelborn, C., Anger, M., & Schickhardt, C. (2023). What is data stewardship? Towards a comprehensive understanding. *Journal of Biomedical Informatics*, *140*, 104337. https://doi.org/10.1016/j.jbi.2023.104337

Whyte, J., Lindkvist, C., & Jaradat, S. (2016). Passing the baton? Handing over digital data from the project to operations. *Engineering Project Organization Journal*, *6*(1), 2–14. https://doi.org/10.1080/21573727.2015.1115396

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering* (pp. 1–10). ACM. https://doi.org/10.1145/2601248.2601268

Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany. (2023). *3D Building Models: ALKIS*. https://www.adv-online.de/AdV-Produkte/Weitere-Produkte/3D-Gebaeudemodelle-LoD/

World Business Council for Sustainable Development, & Boston Consulting Group. (2023). *The EU Digital Product Passport shapes the future of value chains: What it is and how to prepare now*. https://www.wbcsd.org/contentwbc/download/15584/226479/1

Worschech, T. (2024). *Beurteilung der Zukunftsfähigkeit institutioneller Gebäudebestände - ein Beitrag zum Weiterentwicklungsbedarf des Risiko- und Portfoliomanagements* [Dissertation]. Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000168439

Worschech, T., & Lützkendorf, T. (2022). Future proof real estate companies through sustainable development of institutional building stocks – Basics and tools. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 12114. https://doi.org/10.1088/1755-1315/1078/1/012114

Xie, H. S., Brilakis, I., & Loscos, E. (2022). Reality Capture: Photography, Videos, Laser Scanning and Drones. In M. Bolpagni, R. Gavina, & D. Ribeiro (Eds.), *Structural Integrity: Vol. 20. Industry 4.0 for the Built Environment* (Vol. 20, pp. 443–469). Springer International Publishing. https://doi.org/10.1007/978-3-030-82430-3_19

Xu, X., Ma, L., & Ding, L. (2014). A Framework for BIM-Enabled Life-Cycle Information Management of Construction Project. *International Journal of Advanced Robotic Systems*, *11*(8), 126. https://doi.org/10.5772/58445

Yalcin, H., Daim, T., Moughari, M. M., & Mermoud, A. (2024). Supercomputers and quantum computing on the axis of cyber security. *Technology in Society*, *77*, 102556. https://doi.org/10.1016/j.techsoc.2024.102556

Yitmen, I., Alizadehsalehi, S., Akıner, İ., & Akıner, M. E. (2021). An Adapted Model of Cognitive Digital Twins for Building Lifecycle Management. *Applied Sciences (Switzerland)*, *11*(9), 4276. https://doi.org/10.3390/app11094276

Zachman, J. A. (1997). Enterprise Architecture: The Issue of the Century. *Database Programming and Design Magazine*.

Zensusdatenbank. (2024, November 15). *Zensusdatenbank: Gebäude (Gebietsstand 15.05.2022)*. https://ergebnisse.zensus2022.de/datenbank/online/statistic/3000G/details

Zentraler Immobilien Ausschuss. (2015). *Nachhaltigkeit: Kodex, Berichte und Compliance*. Zentraler Immobilien Ausschuss (ZIA).

Zentraler Immobilien Ausschuss. (2023). *Taxonomie der Wirtschaftsimmobilien*. Zentraler Immobilien Ausschuss (ZIA).

Zentraler Immobilien Ausschuss, & EY Real Estate. (2023). *Digitalisierungsstudie 2023: Digitalisierung in der Immobilienbranche: Stockt der Fortschritt?* https://zia-deutschland.de/wp-content/uploads/2023/09/2023_ZIA_EY_Real_Estate_Digitalisierungsstudie.pdf

Zentraler Immobilien Ausschuss, & EY Real Estate. (2024). *Digitalisierungstudie 2024*. https://zia-deutschland.de/wp-content/uploads/2024/09/202493_Digitalisierungsstudie_ZIA_EY.pdf

Zhu, L., Shan, M., & Xu, Z. (2021). Critical review of building handover-related research in construction and facility management journals. *Engineering, Construction and Architectural Management*, *28*(1), 154–173. https://doi.org/10.1108/ECAM-10-2018-0442

Zielinski, J. (2022). Kreation wertstiftender GeschäftsmodelleGeschäftsmodell in neuen Wertschöpfungsformen, Ökosystemen und Plattformen. In C. Jacob & S. Kukovec (Eds.), *Auf dem Weg zu einer nachhaltigen, effizienten und profitablen Wertschöpfung von Gebäuden* (pp. 89–99). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-34962-2_5

Zwirner, M. (2021). Datenbereinigung zielgerichtet eingesetzt zur permanenten Datenqualitätssteigerung. In K. Hildebrand, M. Gebauer, & M. Mielke (Eds.), *Daten- und Informationsqualität* (pp. 101–122). Springer Fachmedien Wiesbaden.

# IV Appendix

# A Appendix chapter 2

## A.1 Real estate management

### A.1.1 Delimitation of the real estate industry

Different terms and definitions regarding the real estate industry can in some cases lead to confusion. The most typical definition in theory and practice is that the real estate industry marks a sub-segment of the economy. Narrowly, it includes companies directly involved in managing, brokering, and administering real estate, along with owner-occupiers and small private landlords. A broader definition extends to all companies contributing to value creation throughout a building's life cycle (Voigtländer et al., 2013, p. 3). This approach aligns with the Federal Statistical Office's classification of economic sectors in Germany (Statistisches Bundesamt, 2008). Accordingly, the real estate industry encompasses construction-related production, part of the secondary (producing) sector, and real estate-related services, within the tertiary sector (Brauer, 2019b, pp. 13–14). These macroeconomic definitions are widely recognized.

A distinctive feature of the real estate industry is its close interdependence with other economic sectors, as many economic activities occur within buildings. This interconnectedness is particularly relevant in the context of climate and environmental protection, where it can be challenging to separate the impacts of real estate activities from those of other industries.

Another classification approach is based on business management theory, distinguishing between activities where real estate is the end product of a service creation process and those where real estate serves as a production factor (Brauer, 2019b, p. 5).

In academic literature, acronyms such as "AEC" (architecture, engineering, and construction industry), "AECO" (including operations), and "AECOO" (adding ownership) are often used. These terms originated from construction and production activities tied to the building life cycle and focus primarily on the building itself. While valid, these terms do not comprehensively capture all activities related to buildings compared to the term "real estate industry."

### A.1.2 Maintenance definition

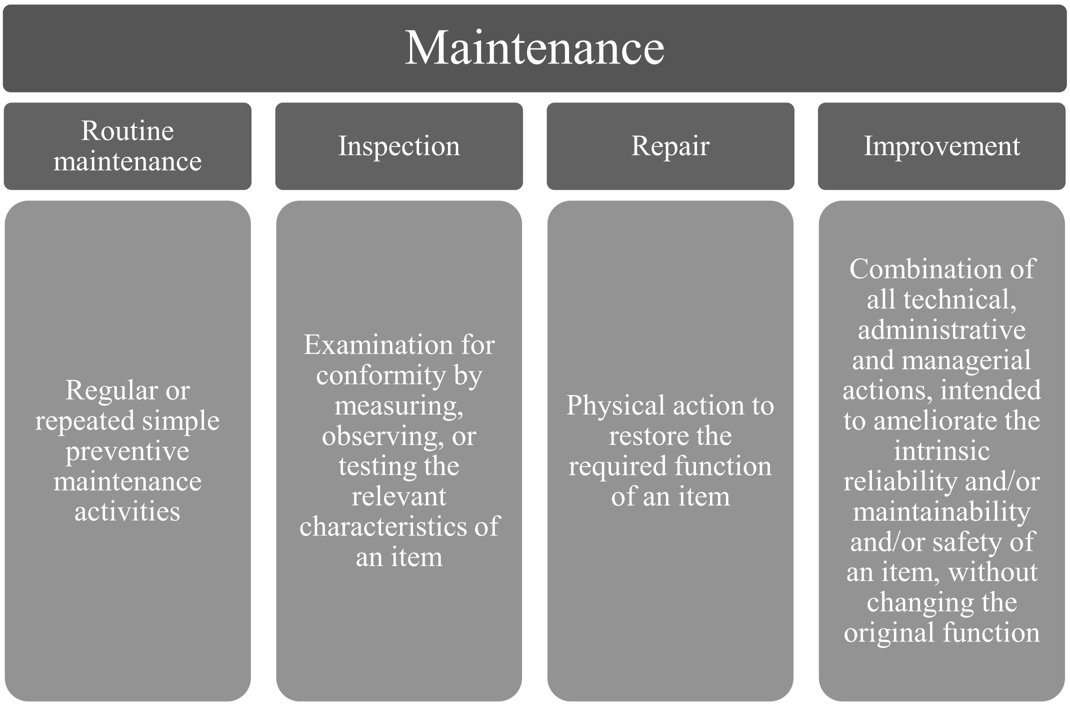



Figure A.1: Types of maintenance based on (DIN EN 13306:2018-02, pp. 41–44)

## A.2 Information modeling

### A.2.1 Information system modeling

Table A.1: The nine principles of information system architecture based on Sunyaev (2020, pp. 27–34)

| Nr. | Principle |
|---|---|
| 1 | An architecture models information system boundaries, inputs, and outputs. |
| 2 | An information system can be broken down into a set of smaller subsystems. |
| 3 | An information system can be considered in interaction with other systems. |
| 4 | An information system can be considered through its entire life cycle. |
| 5 | An information system can be linked to another information system via an interface. |
| 6 | An information system can be modeled at various abstraction levels. |
| 7 | An information system can be viewed along several layers. |
| 8 | An information system can be described through interrelated models with given semantics. |
| 9 | An information system can be described through different perspectives |

## A.2.2 Business modeling

Table A.2: Building blocks in the Business Model Canvas based on Gründerplattform (2025)

| Building block BMC | Relevant |
|---|---|
| Value proposition | What customer needs does the business satisfy? |
| Customer segments | Which customers does it serve? |
| Channels | How does the business communicate and deliver value to the customer? |
| Customer relationships | What type of relationship is created to customers? |
| Revenue streams | How does the business make income from customers? |
| Key activities | Which actions are necessary to execute the value proposition? |
| Key resources | Which resources, such as financial or human resources, are needed? |
| Key partners | Does the business run partner networks to achieve its goals? |
| Cost structure | Which costs occur throughout the business? |

# B Appendix chapter 3

## B.1 Expert interviews and consultations

### B.1.1 Documentation of interviews

The expert interviews and consultations documented in this section were primarily conducted to support the validation of the developed concepts in chapter 8, particularly the information system architecture (ISA) for DBPs (chapter 7). In addition to this validation role, selected insights were retrospectively integrated into earlier chapters (notably chapters 3, 5, and 6) to complement the literature-based analysis with practice-oriented perspectives.

The interviews represent the empirical component of the thesis and aimed to assess the practical relevance, feasibility, and completeness of the proposed concepts from the perspective of professionals in the real estate industry. Eight interviews and consultations were conducted, including academic presentations with open feedback discussions and semi-structured interviews with industry experts.

The interviews followed a semi-structured format based on a guiding framework (section B.1.2), with adaptations made depending on the role and expertise of each interviewee. Interview durations were approximately 45 minutes and covered topics such as data needs, current practices, relevant system functions and technologies, as well as implementation opportunities and challenges.

The following table documents each interview or consultation, including its date, the role of the participant, and the key topics discussed.

Table B.1: Documentation of expert interviews

| Type of consultation | Date | Name event / Role of interview partner | Contents |
|---|---|---|---|
| Conference paper presentation | 13.11.2022 | SBEfin 22 | Presentation and discussion of the historical background on building passports, data requirements, functions, and job-sharing possibilities with other BISs |
| Conference paper presentation | 13.06.2024 | WSBE 24 | Presentation and discussion of the proposal of an ISA for DBPs including the specification of data, functions, user, technology, and process element |

| | | | |
|---|---|---|---|
| Expert interview | 14.11.2024 | Sustainability manager in a municipal housing company | Discussion on potential data needs for sustainability management and housing companies in general; discussion on requirements on a LC-BIS, the elements of the ISA, economic implementation options and challenges associated with that |
| Expert interview | 02.12.2024 | Sustainability manager in a municipal housing company | Discussion on potential data needs for sustainability management and housing companies in general; discussion on elements of the ISA, economic and actor-specific implementation options and challenges associated with that |
| Expert interview | 03.12.2024 | Digitalization manager in a real estate company | Discussion on the use of information systems in real estate companies, the level of digital maturity, and the opportunities and challenges of implementing new information systems |
| Expert interview | 17.01.2025 | Architect in a real estate company | Discussion on data needs for real estate management and on the possibilities to provide these data by planers, on the interconnection between information management and sustainable practices, and on the proposals for the data content of a DBP; discussion on the structure of a DBP and on the potential opportunities and challenges for its practical implementation |
| Expert interview | 24.01.2025 | Asset manager in a real estate fund manager | Discussion on current practices in asset management to collect and manage building-related data, especially in connection with transactions and due diligence; discussion on the proposal of data contents for a DBP, the opportunities and challenges to ensure data quality, and the proposal on implementation roadmaps of different actors |
| Expert interview | 06.02.2025 | Head of property management of a digital property management company | Discussion on the core activities and data needs of property management in comparison to facility and asset management; discussion on the use of BISs and technologies to collect building-related data for property management; discussion on the proposal of data contents in a DBP as well as the opportunities and challenges in terms of practical implementations; Notice on the importance of decision support of BISs |

### B.1.2 Interview guide

This guide was used to conduct semi-structured expert interviews as part of the empirical component of the thesis. The objective of the interviews was to evaluate key concepts, requirements, and architectural considerations for DBPs from the perspective of potential users and stakeholders in the real estate industry.

The interview questions were designed to provide orientation and ensure coverage of core thematic areas relevant to the research. At the same time, a flexible approach was applied to allow for adaptations based on the individual roles, expertise, and experiences of interviewees. Depending on the situational flow of the conversation, questions were sometimes reordered, omitted, or supplemented with follow-up questions to explore specific insights in greater depth.

The interview was typically planned to last around 45 minutes.

The interview guide is structured into the following thematic sections:

**1 Familiarity with the concept**

Have you encountered digital building passports or similar instruments (e.g., building files, house logbooks) in your professional work or otherwise?

If yes:

- What functions or characteristics do you associate with them?
- What have been your experiences so far?

If no:

- Based on the term alone, how would you expect such an instrument to function?

---

**2 Use of Building-related data**

2.1 In your area of responsibility within the real estate industry, what kind of building-related data do you typically need or work with?

2.2 How do you currently access, manage, or store such data?

2.3 Are there any recurring challenges in the way building-related data are handled?

---

**3 Use of Building Information Systems**

3.1 Do you or your organization currently use any digital systems or tools to support building-related information management (i.e. building information systems)?

3.2 If yes:

- Which systems or tools are used?
- What is their primary function and what value do they offer?
- How are different systems distinguished or integrated?

3.3 If no:

- Can you imagine using such a system in the future?
- What conditions would need to be met for you to consider its implementation?

---

## 4 Evaluation of the Proposed Concept

Introductory framing (to be read or briefly summarized by the interviewer):

In this thesis, a digital building passport is defined as a system that supports building owners and other stakeholders in managing building-related information across the entire life cycle of a building.

It integrates functions for collecting, storing, sharing, and using data, aiming to improve information availability, consistency, and quality. Based on this, a requirement profile was developed, outlining what such a system should ideally provide – including core functions (like data storage, documentation, communication), types of building-related data, and the use of modern information technologies.

These elements are brought together in a proposed Information System Architecture (ISA), which structures the passport's components and clarifies its role within the broader ecosystem of digital tools.

*(The concept and visual summary may be presented briefly here)*

4.1 Based on this understanding, how do you assess the overall **relevance and practical value** of a digital building passport for your work or the industry more broadly?

4.2 Do the **proposed functions** align with what you would expect from such a system? Are there key functions that should be added, modified, or removed?

4.3 Regarding the **building-related data**, which data types do you consider essential for inclusion in a building passport? Are there data you consider less important or difficult to maintain?

4.4 From a technical perspective, which **information technologies or features** (e.g. digital access, data interoperability, integration with other systems) do you view as particularly important for the system to work effectively in practice?

4.5 *(Optional)* One idea in the architecture is that the passport could act as a **building-level interface**, coordinating with other digital tools (e.g. BIM, BAMS). What would be necessary, in your view, to make such a setup feasible?

---

**5 Implementation Opportunities and Risks**

5.1 What do you see as the main opportunities for implementing digital building passports (e.g., technical, economic, or organizational benefits)?

5.2 What are the biggest challenges or risks that need to be addressed for successful implementation and adoption?

---

**6 Open Reflection**

6.1 Are there any additional aspects or concerns you would like to raise regarding the topic?

6.2 Based on the proposed concept, how would you assess the chances for broader dissemination and practical use of digital building passports?

## B.2 Specifications of regulatory systems for data creation and collection

### B.2.1 Construction documentation based on HOAI

Table B.2: Basic and special services for buildings and interiors within the HOAI based on (HOAI, 2013)

| Phase | Basic services | Examples of Special services |
|---|---|---|
| 1. Basic evaluation | Clarify objectives, site inspection, summarize results. | Needs assessment, site analysis, feasibility studies. |
| 2. Preliminary design | Develop preliminary design, cost estimation, prepare schedule. | Alternative solutions, financing plans, room books. |

| | | |
|---|---|---|
| 3. Design development | Refine design, cost calculation, update schedule. | Cost investigations, updating room books, economic analysis. |
| 4. Approval planning | Prepare and submit approval documents, adjust designs as required. | Assistance with consents, technical proofs, legal support. |
| 5. Construction drawings | Prepare detailed plans, coordinate with participants. | Review contractor plans, material planning. |
| 6. Preparation of tendering | Create specifications, bill of quantities, compile tender documents. | Advanced cost breakdowns, alternative specifications. |
| 7. Participation in tendering | Evaluate bids, compare prices, prepare award proposals. | Review alternative offers, financial planning support. |
| 8. Construction supervision and documentation | Monitor construction, track costs, compile object documentation. | Progress reporting, cost control, health and safety oversight. |
| 9. Object support | Warranty monitoring, inform client, coordinate measures. | Maintenance regulations, technical evaluations, defect review. |

## B.2.2 Construction documentation based on DIN report 151

Table B.3: Document section of a construction documentation (DIN Fachbericht 151:2007-01)

| Level 1: Documentation Sections | Level 2: Document Groups |
|---|---|
| A - Agreements and Invoicing for Architect, Engineer, and Specialist Fees | A1 - General and Specialized Planning,<br>A2 - Specialized Planning,<br>A3 - Specialist Services |
| B - Integrated Construction and Permitting Planning | B1 - Object Planning and Associated Specialized Planning |
| C - Construction Preparation and Execution for Building Structures | C1 - Safety and Preparatory Measures,<br>C2 - Excavation and Foundations,<br>C3 - Wall and Ceiling Structures,<br>C4 - Roof Structures,<br>C5 - Floor Coverings |
| D - Construction Preparation and Execution for Technical Installations | D1 - Ventilation Systems,<br>D2 - Heating and Hot Water Systems,<br>D3 - Gas, Water, and Sewage Systems,<br>D4 - Electrical Systems |
| E - Construction Preparation and Execution for External Areas | E1 - Safety Measures for External Areas,<br>E2 - Terrain and Paved Surfaces,<br>E3 - Structures in External Areas |

### B.2.3 Use documentation based on DIN 32835-2

Table B.4: Document sections of a use documentation (DIN 32835-2:2007-01)

| Level 1: Documentation Sections | Level 2: Document Groups |
|---|---|
| A - Representing and Maintaining Building and Facility Structures | A1 - Building Book,<br>A2 - Asset Book |
| B - Representing and Maintaining the Building's Usage Structure | B1 - Room Sheets for Primary Uses,<br>B2 - Room Sheets for Secondary Uses |
| C - Representing and Maintaining the Structures of Furnishings and Equipment | C1 - Furnishing and equipment Book,<br>C2 - Fixture and fittings Book |
| D - Managing the Usage and Utilization of Available Building Areas | D1 - Determining Space Requirements,<br>D2 - Space Formation,<br>D3 - Creation of Rentable Units,<br>D4 - Occupancy and Relocation Planning |
| E - Acceptance and Maintenance of Building Structures | E1 - Handover/Acceptance of New Buildings,<br>E2 - Handover/Acceptance of Existing Structures,<br>E3 - Maintenance and Inspection of Special Structures,<br>E4 - Repair of Building Structures |
| F - Operating and Maintaining Technical Facilities | F1 - Commissioning and Starting Operations,<br>F2 - Maintenance and Inspection,<br>F3 - Troubleshooting and Workflow Restoration,<br>F4 - Addressing Technical Failures,<br>F5 - Decommissioning Technical Facilities |
| G - Ensuring Order and Cleanliness | G1 - Building Administration,<br>G2 - Cleaning and Maintenance of Floors, G3 - Glass Cleaning,<br>G4 - Facade Treatment, G5 - Sanitary Maintenance,<br>G6 - Waste Disposal and Pest Control,<br>G7 - Outdoor Area Maintenance,<br>G8 - Parking Services |
| H - Monitoring and Securing the Building | H1 - Building Security,<br>H2 - Fire Safety,<br>H3 - Emergency Assistance,<br>H4 - Staff Training for Safety |
| I - Supplying the Building with Utilities | I1 - Water, Gas, and Sewage Systems,<br>I2 - Heating, Cooling, and Air Systems,<br>I3 - Power Supply |
| K - Designing and Implementing Communication Systems | K1 - Use of Technical Information Systems, K2 - Organization of Communication Systems |

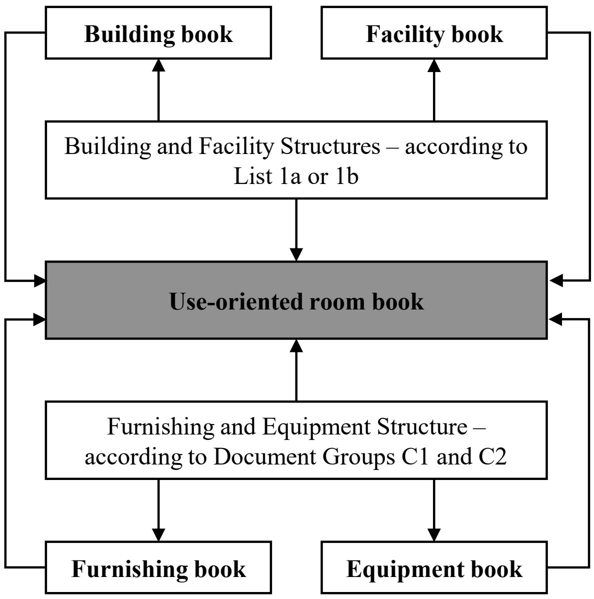



Figure B.1: Structure of description systems for a use documentation in facility management (DIN 32835-2:2007-01, p. 17)

# B.3 Decisions throughout the building life cycle

Table B.5: Relevant decisions and basis for decisions in the building life cycle

| | | Important decisions | Decision basis |
|---|---|---|---|
| Life cycle stage | Development and construction | Project initiation | Perception of a need for new construction |
| | | Project realization | Successful feasibility and profitability assessment |
| | | Design | Needs assessment, regulation, and stakeholders (e.g. building operators or users) |
| | | Building permit | Building permit documents |
| | | Approval of funding | Proof of fulfillment of funding requirements |
| | | Project management decisions | Requirements by actors involved in construction and skills of executing actors |
| | | Handover and final acceptance | Final inspection |
| | Use | Maintenance works | Scheduled intervals, data analysis and monitoring, failure or malfunction, current condition of components, eliminating root causes, safety risk |
| | | Modernization, refurbishment, retrofitting | Outdated facilities, inefficient or excessive resource use (especially energy), excessive emissions, negative impacts on environment or people |
| | | Repurposing | Change in (market) needs |
| | | Space allocation and reconfiguration decision | Change in (market) needs |

| | | | |
|---|---|---|---|
| | | Rental decisions of owners | Evaluation of the satisfaction of requirements |
| | | Rental decisions of tenants | Evaluation of the satisfaction of needs |
| | | Interior design decisions | Evaluation of the satisfaction of needs |
| | End-of-life | End-of-use decision | Economic or technical reasons |
| | | Permit for deconstruction | Compliance with legal requirements on deconstruction |
| | | Type of deconstruction | Preferences of the building owner and framework conditions |
| | | Waste processing | Quality of building components and materials including economic and environmental aspects |
| | | Project management decisions | Requirements of the building owner, preferences of project managers |
| | | Further use of property | Preferences of the building owner, use potential of the property, legal requirements |

# B.4 Use-oriented occasions of information demand

Table B.6: Examples for use-oriented occasions of information demand for selected building use types

| Office | Retail | Industry and logistics |
|---|---|---|
| Redesign of office furniture<br>Conversion of building spaces<br>Installation of air-conditioning<br>Redesign of power supply and lighting<br>Monitoring the indoor climate<br>… | Redesign of sales area<br>Redesign of power supply and lighting<br>Monitoring the indoor climate<br>… | Use of new machines, technologies or inventory<br>Redesign of transport routes<br>Monitoring the indoor climate<br>Repurposing of work areas<br>… |

## B.5 Actor roles in building-related tasks

Table B.7: Actor roles in building-related tasks

| Main perspective | Actor roles involved | Development and construction | Use and operation | End-of-life | Valuation | Risk management | Marketing | Public sector tasks | Sustainability assessment and management | Non-financial reporting |
|---|---|---|---|---|---|---|---|---|---|---|
| Return-oriented | Building owners | (x) | x | (x) | (x) | x | (x) | | x | x |
| | Landlords | (x) | x | (x) | (x) | x | (x) | | x | x |
| | Investment managers | (x) | x | (x) | (x) | x | (x) | | x | (x) |
| | Portfolio managers | (x) | x | (x) | (x) | x | (x) | | x | (x) |
| | Asset managers | (x) | x | (x) | (x) | x | (x) | | x | (x) |
| | Property managers | | x | | (x) | (x) | | | (x) | (x) |
| | Facility managers | | x | | | | | | (x) | (x) |
| | Financiers, banks | (x) | (x) | (x) | (x) | x | | | x | x |
| | Insurer | (x) | (x) | (x) | (x) | x | | | (x) | (x) |
| | Real estate agents | (x) | (x) | | | | x | | | |
| Performance-oriented | Building product manufacturers | x | (x) | x | | | | | (x) | |
| | Project developers | x | (x) | x | | | | | (x) | |
| | Project managers | x | (x) | x | | | | | (x) | |
| | Planers | x | (x) | x | | | | | x | |
| | Construction companies | x | (x) | x | | | | | (x) | |
| | Craftsmen | x | (x) | x | | | | | | |
| | Energy consultants | x | (x) | x | | | | | x | |
| | Building experts and surveyors | x | (x) | x | x | | | | (x) | |
| | Auditors and certifiers | x | (x) | x | | | | | x | |
| | Utility companies | x | (x) | x | | | | | (x) | |
| | Facility services | | x | | | | | | | |
| | Billing service providers | | (x) | | | | | | | |

| Main perspective | Actor roles involved | Development and construction | Use and operation | End-of-life | Valuation | Risk management | Marketing | Public sector tasks | Sustainability assessment and management | Non-financial reporting |
|---|---|---|---|---|---|---|---|---|---|---|
| | Waste management companies | x | (x) | x | | | | | | |
| Use-oriented | Institutional owner-occupiers | (x) | x | (x) | (x) | (x) | (x) | | x | x |
| | Institutional tenants | | x | | | | | | (x) | (x) |
| | Individual owner-occupiers | (x) | x | (x) | (x) | (x) | (x) | | (x) | |
| | Individual tenants | | x | | | | | | | |
| Public sector | Building authority | x | (x) | x | (x) | | | x | (x) | |
| | Legislator | (x) | (x) | (x) | (x) | | | x | (x) | x |
| | Society | (x) | (x) | (x) | | | | | (x) | (x) |
| | Neighbors | (x) | (x) | (x) | | | | | | |

# B.6 Evidence of building-related data needs

This section compiles evidence from various sources to substantiate the relevance of specific data needs throughout the building life cycle. The information is organized by key task areas and life cycle stages to ensure clarity and traceability. For each task area, the respective tables reference relevant sources, indicating whether a specific data need is directly addressed, implicitly mentioned, or not referenced. The legend used in the tables is as follows:

- x: Clear reference in the source
- (x): Implied or indirect reference in the source
- (blank): No reference found in the source

### B.6.1 Development and construction

Table B.8: Evidence of data needs in development and construction

| | | HOAI, 2013 | Building permit documentation | VDI 6026:2015-04 part 1.1 | DIN Fachbericht 151:2007-01 | VDI 6070 Part 1 | VDI 6039:2011-06 |
|---|---|---|---|---|---|---|---|
| Master data | Identifiers (Building, rooms) | | | | | x | |
| | Building usage | | x | x | | x | (x) |
| | Actor information | x | x | | | | (x) |
| | Location and site data | x | (x) | | x | | |
| | Planning log (needs assessment, feasibility, coordination...) | x | (x) | | x | | |
| | Construction log (site progress, acceptance, inspections...) | x | | | x | | (x) |
| | Maintenance schedule | | | x | | | (x) |
| Inventory data | Area data | (x) | (x) | (x) | | x | (x) |
| | Building component descriptions and properties | (x) | (x) | x | x | (x) | |
| | Building geometry | x | x | (x) | x | x | |
| | Building services descriptions and properties | (x) | (x) | x | x | (x) | (x) |
| | Building services testing documentation | (x) | | x | x | | x |
| | Building services maintenance instructions | x | | | x | | (x) |
| | Outdoor facilities documentation | (x) | (x) | | x | (x) | |
| | Photo documentation | | | x | | | |
| | Property plans, floor plans, site maps | x | x | x | x | | |
| | Room (book) information | x | | x | | x | |
| | Fixtures and fittings documentation | | | x | | x | |
| | Furnishing and equipment documentation | | | | | x | |
| Economic and legal | Construction costs (planning, budgeting, determination) | x | | (x) | x | | |
| | Contracts (rental, construction, maintenance, utility supply…) | x | | x | x | | |
| | Service agreements (planning and construction) | x | | | x | | |
| | Building permits and approvals | x | x | x | x | | |
| | Insurance policies | | | x | | | |
| | Bills and invoices | | | | x | | |
| Perf. data | Energy efficiency | | x | (x) | | | |
| | Environmental quality | (x) | (x) | (x) | | | |
| | Environmental impacts | x | (x) | | | | |

## B.6.2 Use and operation

Table B.9: Evidence of data needs during use and operation

| | | DIN 32835-2:2007-01 | VDI-MT 3810 Part 1:2023- | VDI 6041:2017-07 | DIN SPEC 91462:2022-02 | RICS (2020) | RICS (2022a) |
|---|---|---|---|---|---|---|---|
| Master data | Building usage | x | | x | x | x | x |
| | Actor information | | x | (x) | x | | (x) |
| | Location and site data | x | | | (x) | x | |
| | Planning record | x | x | (x) | x | | |
| | Construction and commissioning record | x | x | (x) | x | x | |
| | Maintenance log and plan | x | x | (x) | x | x | |
| | Property management log | x | | | x | | |
| | Usage log and instructions | | x | (x) | x | | |
| Inventory data | Area data | | x | (x) | | (x) | x |
| | Building component descriptions and properties | x | (x) | | x | x | |
| | Building component conditions and deficiencies | | | | x | | |
| | Building geometry | x | (x) | | (x) | (x) | |
| | Building services descriptions and properties | x | x | (x) | x | x | |
| | Building services testing documentation | x | x | (x) | (x) | | |
| | Building services operating and maintenance instructions | x | x | (x) | x | | |
| | Building services conditions | | | x | | | |
| | Outdoor facilities documentation | | | | | x | (x) |
| | Photo documentation | | x | | | | |
| | Room (book) information | x | x | | | | |
| | Fixtures and fittings documentation | x | | | | | |
| | Furnishing and equipment documentation | x | x | | | | |
| | Security and fire protection facilities documentation | x | x | (x) | | x | |
| | Heating and energy supply systems properties | x | | | | | |
| | Information and communication systems properties | x | x | | | | |
| | Accessibility and inclusiveness | | | | | x | |
| | Hazardous materials | | | | | x | |
| Economic | Operating and maintenance costs | x | | (x) | x | | x |
| | Life cycle costs | | | | | | x |
| | Contracts (construction, rental, service providers…) | x | x | | x | | |
| | Rental information | | | | | | |

| | | DIN 32835-2:2007-01 | VDI-MT 3810 Part 1:2023- | VDI 6041:2017-07 | DIN SPEC 91462:2022-02 | RICS (2020) | RICS (2022a) |
|---|---|---|---|---|---|---|---|
| | Building permits and approvals | | x | | | x | |
| | Bills and invoices | x | | x | | | |
| | Cultural heritage, statuary protection | | | | | x | |
| Performance data | Energetic quality | | | (x) | (x) | x | |
| | Environmental label, rating system | | | | | x | |
| | Indoor enrivonmental parameters (temperature, CO2, noise…) | | | x | | | x |
| | Occupant behavior data | | | x | | | |
| | User satisfaction data | | | x | | | x |
| | Energy flows including energy consumption | | | x | | | x |
| | Material flows including wastes | | | | | | x |
| | Social value | | | | | | x |

### B.6.3 End-of-life

Table B.10:Evidence of data needs at the end-of-life stage

| | | BMI and BMVg (2018) | VDI 6210:2024-10 part 1 | Osberghaus (2008) |
|---|---|---|---|---|
| Master data | Building usage | x | x | x |
| | Actor information | x | | |
| | Location and site data | x | | x |

| | | BMI and BMVg (2018) | VDI 6210:2024-10 part 1 | Osberghaus (2008) |
|---|---|---|---|---|
| | Planning record | (x) | (x) | |
| | Construction and commissioning record | (x) | (x) | (x) |
| | Maintenance record | (x) | x | |
| | Usage record | (x) | x | x |
| | Deconstruction log | x | x | x |
| Inventory data | Area data | x | (x) | (x) |
| | Building component descriptions and properties | x | x | x |
| | Building component conditions and deficiencies | x | (x) | (x) |
| | Building geometry | x | | (x) |
| | Building services descriptions and properties | x | x | x |
| | Building services conditions | x | (x) | (x) |
| | Floor plans, detail plans | | x | |
| | Outdoor facilities documentation | x | x | |
| | Furnishing and equipment documentation | | x | |
| | Photo documentation | (x) | (x) | |
| | Security and fire protection facilities documentation | x | | |
| | Heating and energy supply systems properties | x | | |
| | Hazardous materials | x | x | x |
| | Building elements disposal instructions | x | x | x |
| Economic and legal data | Costs for deconstruction / demolition | x | x | |
| | Costs for disposal and recycling | x | x | |
| | Contracts for deconstruction and waste processing | x | | x |
| | Building permit for deconstruction | | x | |
| | Approvals for waste disposal | x | | |
| | Cultural heritage, statuary protection | x | x | |
| Performance data | Risks for environmental pollution | | x | |
| | Recycling and reuse potential of building elements | | x | |
| | Material flow balance | | x | |

### B.6.4 Valuation

Table B.11:Evidence of data needs for property valuation

| | | Meins et al. (2011) | Schlachter (2019) | IAAO (2018) |
|---|---|---|---|---|
| Master data | Building usage | x | x | x |
| | Location data (macro and micro location) | x | x | x |
| | Site data | x | x | x |
| | Building (element) age | | x | x |
| | Number of apartments | | x | |
| | Planning record (process quality) | (x) | | |
| | Construction record (process quality) | (x) | | |
| | Maintenance record | (x) | (x) | |
| Inventory data | Area data, size of property and building | x | x | x |
| | Floor plans | (x) | x | |
| | Building condition | (x) | (x) | x |
| | Quality of construction | (x) | | x |
| | Heating system | x | x | |
| | Room book information | | x | |
| | Equipment and features | x | x | |
| | Fixtures | | x | |
| | Material properties | x | x | |
| | Outdoor facilities | x | x | |
| | Technical properties (e.g. fire protection) | x | | |
| | Functional properties (e.g. adaptibility, accessibility) | x | | |
| | Asthetic quality | x | | |
| Economic and legal data | Rights of use | | x | |
| | Tenancy law ties | | x | |
| | Cultural heritage, statuary protection | x | | |
| | Rental cash flows | x | | |
| | Value development potential | x | | |
| | Building encumbrances | | x | |
| | Operating costs and revenues | x | | |
| Performance data | Energetic characteristics | x | x | |
| | Resource utilization (energy, materials) | x | | |
| | Environmental impacts (global, local | x | | |
| | Wastes | x | | |

| | | Meins et al. (2011) | Schlachter (2019) | IAAO (2018) |
|---|---|---|---|---|
| | Health, comfort, satisfaction of occupants | x | | |
| | Certifications and quality labels | x | | |

## B.6.5 Risk management

Table B.12:Evidence of data needs for risk management

| | | VÖB-Kommission für Bewertungsfragen (2006) | Urschel (2010) | NV-Versicherungen | Kiedrowski |
|---|---|---|---|---|---|
| Master data | Building usage | x | (x) | x | x |
| | Actor information | x | (x) | x | x |
| | Location and site data | x | x | x | x |
| | Planning record | (x) | | | |
| | Contruction record including year of construction | x | (x) | (x) | (x) |
| | Maintenance record | x | | (x) | x |
| | Number of apartments | | | x | |
| Inventory data | Building (component) description | x | x | x | x |
| | Floor plans | x | x | | |
| | Area data | | | | x |
| | Building services desrciption | x | x | | x |
| | Building materials | x | | | x |
| | Geometry and architecture | | x | | |
| | Outdoor facilities documentation | x | x | | |

| | | VÖB-Kommission für Bewertungsfragen (2006) | Urschel (2010) | NV-Versicherungen | Kiedrowski |
|---|---|---|---|---|---|
| | Security facilities | | x | | |
| | Furnishing and equipment documentation | | | | x |
| | Functional characteristics, e.g. adaptibility, flexibility | x | x | | |
| | Space efficiency | x | x | | |
| | Accessibility | x | | | |
| Economic and legal | Operating costs | x | | | |
| | Rental revenues | x | | | |
| | Rent development potential | x | | | |
| | Property value development potential | x | x | | |
| | Property value | | | | x |
| | Rental contracts | x | | | |
| | Profitability | | x | | |
| Performance | Assessment of quality of building elements | x | | | |
| | Energy performance | x | | | |
| | Emissions | x | | | |
| | Environmental impacts | x | x | | |

## B.6.6 Marketing

Table B.13:Evidence of data needs for real estate marketing

| | | Helfrich (2021) | Real estate listings[1] | Real estate brochures[1] |
|---|---|---|---|---|
| Master data | Building usage | | x | x |
| | Actor information | x | x | (x) |
| | Location data | (x) | (x) | (x) |
| | Year of construction | | (x) | (x) |
| | Year of last maintenance | | (x) | (x) |
| | Living space calculation | x | | |
| | Number of apartments | | (x) | (x) |
| Inventory data | Building description | x | x | x |
| | Elevation drawings, floor plans | x | x | x |
| | Area data | (x) | x | x |
| | Photo documentation | | x | (x) |
| | Outdoor facilities documentation | | (x) | (x) |
| | Furnishing and equipment documentation | | (x) | (x) |
| | Functional characteristics, e.g. adaptibility, flexibility | | (x) | (x) |
| | Space efficiency | | (x) | (x) |
| | Accessibility | | (x) | (x) |
| Economic and legal data | Brokerage contract | x | | |
| | Land register extract | x | | |
| | Parcel maps from land registers | x | | |
| | Utility bill statement | x | | |
| | Leasehold contract | x | | |
| | Rent | | x | x |
| | Property value / sales price | | | x |
| Performance data | Energy performance (certificate) | x | (x) | (x) |

[1] To identify data needs, a considerable number of real estate listings and brochures related to sales and rentals were examined on various web portals, including:

- https://www.immobilienscout24.de/
- https://www.engelvoelkers.com/de/en
- https://immocenter-karlsruhe.de/immobilienangebote/
- https://www.immowelt.de/

## B.6.7 Public sector tasks

Table B.14:Evidence of building-related data needs by the public sector in its role as legislator

| | | Krause et al. (2022) | Zensusdatenbank (2024) | Danish Building and Dwelling Register[1] | Swiss Property Register[2] |
|---|---|---|---|---|---|
| Master data | Identification (building ID, apartment ID) | x | | x | x |
| | Location and address | x | | x | x |
| | Site data | | | (x) | x |
| | Actor information (owners, occupiers) | x | x | | x |
| | Building usage | x | x | x | x |
| | Vacancy | | x | | x |
| | Year of construction | x | x | x | |
| | Construction record | x | | | x |
| | Maintenance record | | | x | x |
| Inventory data | Construction method | | x | x | |
| | Building size | | x | x | |
| | Layout | | | x | |
| | Area data (usable area, living area) | x | x | x | x |
| | Envelope area | | | x | |
| | Heating system | x | x | x | x |
| | Energy source | x | x | x | x |
| | Renewable energy use | x | | (x) | x |
| | Location of apartment in building | x | | | x |
| | Building services description | | | x | |
| | Building materials | | | x | |
| | Hazardous materials | | | x | |
| | Outdoor facilities documentation | | | x | |
| | Utility supply | | | x | x |
| | Furnishing and equipment documentation | | | (x) | (x) |
| | Fixture and fittings documentation | | | (x) | (x) |
| Economic and legal data | Property rights | x | | x | |

| | | Krause et al. (2022) | Zensusdatenbank (2024) | Danish Building and Dwelling Register[1] | Swiss Property Register[2] |
|---|---|---|---|---|---|
| | Apartment rent | | x | | |
| | Cultural heritage, statuary protection | | | x | |
| | Insurances (e.g. indemnity) | | | x | |
| | Building permit and approvals | | | x | |
| | Building permit process record | | | | x |

[1] Sources: (*The Central Register of Buildings and Dwellings (BBR)*, 2025; *Datamodel*, 2025; *Grunddataordbog*, 2024)

[2] Source: Bundesamt für Statistik (2022)

### B.6.8 Sustainability assessment and management

Table B.15:Important standards for sustainability assessments of buildings

| Standard | Scope and reference to building-related data |
|---|---|
| ISO 15392:2019-12 | Higher-level standard for the definition of general principles on sustainability of buildings |
| ISO 21931-1:2022-06 | Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment; includes specifications on important assumptions and system boundaries |
| ISO 21929-1:2011-11 | Specification of a general framework for indicators in sustainability assessment including the definition of a core set of indicators |
| ISO 16745-1:2017-05 | Guidelines to determine GHG emissions during the use stage of a building |
| DIN EN 15978:2024-05 | Methodology to assess the environmental quality of a building including references to indicators from LCAs |

| | |
|---|---|
| DIN EN 16627:2015-09 | Methodology to assess the economic quality of a building including specifications of costs and revenues throughout the life cycle |
| DIN EN 16309:2014-12 | Methodology to assess the social quality of a building |
| DIN SPEC 91475:2024-03 | Specification of commonly used indicators to assess the environmental quality of buildings including relevant raw data |

Table B.16:Evidence of data needs for sustainability assessment

| | | DIN EN 16627:2015-09 | DIN EN 15978:2024-05 | DIN EN 16309:2014-12 | DIN SPEC 91475:2024-03 | NaWoh (2024) | GRESB Real Estate (2025) |
|---|---|---|---|---|---|---|---|
| Master | Building usage | | | | | x | |
| | Location and site data | | (x) | | | x | |
| | Mobility infrastructure | | | x | | x | |
| | Actor information | | | | | (x) | (x) |
| Inventory data | Area data | | (x) | (x) | | x | |
| | Building element properties | | (x) | (x) | (x) | (x) | |
| | Building material reuse / recycling potential | | x | | x | x | (x) |
| | Resilience against natural hazards | | | x | x | x | x |
| | Building services controllability | | | x | | | |
| | Accessibility | | | x | | | |
| | Space efficiency | | | x | | x | |
| | (Non-)hazardous materials | | | x | | | |
| | Indoor lighting | | | x | | x | |
| | Compact building design | | | | x | | |
| | Longevity and adaptability | | | | x | x | |
| | Summer thermal insulation | | | | x | x | x |
| | Low-temperature capability of heating system | | | | (x) | | |
| | Airtightness | | | | | x | |
| | Use of green roof area potential | | | | | | x |
| | Renewabke energy integration | | | | (x) | | x |
| Econo | Life cycle costs | x | | | | x | (x) |
| | Construction costs | x | | | | (x) | x |
| | Operational costs | x | | | | (x) | x |

| | | DIN EN 16627:2015-09 | DIN EN 15978:2024-05 | DIN EN 16309:2014-12 | DIN SPEC 91475:2024-03 | NaWoh (2024) | GRESB Real Estate (2025) |
|---|---|---|---|---|---|---|---|
| | Profitability (e.g. Net present value) | x | | | | x | |
| | Revenues | | | | | x | |
| | Property value | | | | | x | x |
| Performance data | Energy usage | | x | | x | (x) | x |
| | Energy performance (prediction) | | x | | x | x | x |
| | Global warming potential (GWP) | | x | | x | x | x |
| | GHG emissions | | x | | x | (x) | x |
| | Other LCA impact indicators | | x | | x | | |
| | Fresh water use | | x | | x | x | |
| | (Hazardous) wastes | | x | | x | x | |
| | Local environmental impacts | | x | x | x | | |
| | Indoor environmental quality | | | x | x | | |

## B.6.9 Non-financial reporting

*Background EU taxonomy*: There are six environmental goals in the EU taxonomy. In order to classify an economic activity as sustainable, the operator of the activity must choose one environmental goal and check the technical screening criteria (TSC) that are defined for different sector activites. In addition, it must be checked whether the activity meets "Do Not Significant Harm" (DNSH) criteria for other environmental goals (EU taxonomy regulation, 2020; Climate Delegated Act, 2021; Environmental Delegated Act, 2023). In Table B.17, an overview is given on requirements that need to be met for the economic activity "renovation of existing buildings".

Table B.17: Environmental goals and indicators in the EU taxonomy for the economic activity “renovation of existing buildings” (Climate Delegated Act, 2021)

| Environmental Goal | Requirements | Type of criteria (TSC or DNSH) |
|---|---|---|
| Climate change mitigation | Reduce primary energy demand by at least 30% compared to pre-renovation levels and comply with national definition on major renovations | TSC |
| Climate change adaptation | Assess vulnerability to climate risks and develop action plans for necessary adaptations | DNSH |
| Sustainable use of water and marine resources | Use water-saving devices and technologies during renovation that do not exceed specific maximum water flows | DNSH |
| Transition to a circular economy | At least 70% of non-hazardous construction and demolition waste is prepared for reuse or recycling | DNSH |
| Pollution prevention and control | Emission of less than 0,06 mg of formaldehyde per m3 of material or component and less than 0,001 mg of other carcinogenic volatile organic compounds per m3 of material or component | DNSH |
| Protection and restoration of biodiversity and ecosystems | No specific requirement | DNSH |

Table B.18:Evidence of data needs for non-financial reporting

| | | Climate Delegated Act, 2021 | SFDR, 2019 | CSRD directive, 2022 |
|---|---|---|---|---|
| Master data | Location data | | (x) | (x) |
| | Costruction record | (x) | | |
| | Actor information | (x) | (x) | (x) |
| | Building usage | | | (x) |
| Inventory data | Energy source and heating system | (x) | (x) | (x) |
| | Air tightness | x | | |
| | Building envelope quality | x | | |
| | Resilience against climate risks | x | | x |
| | Primary raw material share / consumption | x | x | (x) |
| | Water fittings properties | x | | |
| | Circular building design | x | | |
| | Harmful substances in building materials | x | | (x) |
| | Use of green roof area potential | | x | |
| | Land artificialisation | | x | (x) |
| | Recycling and reuse potential | | | (x) |
| | Functional building qualities | | | (x) |
| Economic and legal data | Operational costs | (x) | | (x) |
| | Revenues, e.g. rent | (x) | | (x) |
| | Projected investments costs | | | x |
| | External costs | | | (x) |
| | Property value | | | (x) |
| | (Internal) carbon prices | | | (x) |
| Performance data | Primary energy demand | x | x | x |
| | Energy performance | | x | x |
| | Life cycle GWP | x | | (x) |
| | Energetic quality (national standard) | x | x | (x) |
| | Recycling share of construction wastes | x | | (x) |
| | Impacts on local environment and biodiversity | x | x | (x) |
| | GHG emissions (scope 1-3) | | x | x |
| | GHG intensity (e.g. GHG emissions / enterprise value) | | x | x |
| | Carbon footprint | | x | |

| | | Climate Delegated Act, 2021 | SFDR, 2019 | CSRD directive, 2022 |
|---|---|---|---|---|
| | Share of non-renewable energy consumption | | x | x |
| | Energy consumption intensity | | x | |
| | Emissions to water | | x | (x) |
| | Waste production in operations | | x | (x) |
| | Hazardous wastes ratio | | x | (x) |
| | Emissions to air, e.g. inorganic pollutants | | x | (x) |
| | Water usage and recycling | | x | (x) |
| | Other LCA indicators | | | (x) |
| | Fossil fuel use | | | (x) |

# B.7 Taxonomy of building-related data points

## B.7.1 Master data

Table B.19:Building-related data needs in the master data category

| Nr. | Data category and data points | Description |
|---|---|---|
| **100** | **Master data** | General data on the building, property, apartment etc. functioning as spatial, temporal, and actor-based context for many other data points |
| 110 | Identification | Data points that facilitate the unambiguous identifiation of objects on different levels of aggregation and from different perspectives; important to establish relationships between different data points and systems |
| 111 | National building register identifier | ID in the context of national building registers |
| 112 | Corporate identifier | ID in the context of corporate building stocks; more than one possible |
| 113 | Apartment / unit identifier | ID for apartments or other types of units within a building |

| Nr. | Data category and data points | Description |
|---|---|---|
| 114 | Room identifiers | IDs for rooms and spaces within a building |
| 115 | Building element identifiers | IDs for all types of building elements including structural building components and building services |
| **120** | **Building usage** | Data that are necessary and helpful to understand how a building is used |
| 121 | Building use type | Type of building usage based on a classification of building use types and optional descriptions |
| 122 | Building type specification | Further details on the type of building, e.g., single-family house, multi-family house, terraced house etc. |
| 123 | Building unit use type | Type of building unit usage based on a classification of building use types and optional descriptions |
| 124 | Building use areas | Type of building area usage based on description |
| 125 | Owner occupation or rental | Indication whether a building or unit is owner-occupied or rented |
| 130 | **Actor information** | Data on actors associated with the building |
| 131 | Building owner data | General data on the current owner of a building or building unit, such as name or contact details |
| 132 | Ownership history | General data on former building owners |
| 133 | Planning and construction actors | Data on actors involved in contruction, such as name, contact details, role, services |
| 134 | Real estate management actors | Data on actors involved in real estate management, such as name, contact details, role, services |
| 135 | Service providers (facility services) | Data on executing service providers, such as name, contact details, role, services |
| 136 | Local building authority | Basic data on the resonsible local building authority |
| 140 | **Important dates** | Dates that mark outstanding events in the building's history |
| 141 | Construction | Year(s) of construction |
| 142 | Transactions | Dates of purchases /sales |
| 143 | As-built constructions and renovations | Year(s) of major as-built constructions and renovations |
| 144 | Rentals | Dates of (new) rentals |
| 145 | Repurposing | Dates of use changes / repurposing |
| 150 | **Location and site data** | Specification of geographical and spatial positioning and relevant characteristics of the location |
| 151 | Address | Postal code, street, building number |
| 152 | Geocoordinates | Specification of geographical position |
| 153 | Climate and environmental data | Data about the climate and the environment at the building location including climate forecasts |

| Nr. | Data category and data points | Description |
|---|---|---|
| 154 | Exposure to climate risks and natural hazards | Based on the location and, e.g., based on linkages to GISs; evaluations are possible in connection with inventory data, especially functional building properties |
| 155 | Spatial context data | Typical data subject to location analyses, e.g., urban context, access to key services |
| 156 | Site data | Aspects directly related to the property and its immediate surroundings, e.g., topography and soil conditions |
| 160 | **Planning record** | A structured dataset containing documentation, decisions, and analyses from the planning stage, providing a reference for later life cycle stages |
| 161 | Needs assessment | Documented requirements, functional and spatial needs, regulatory constraints, and user expectations that guided the initial planning phase |
| 162 | Feasibility analyses | Results of evaluations of technical, legal, and economic feasibility with the help of market analyses, site analyses, use concept analyses etc. |
| 163 | Cost-benefit analyses | Calculations, financial assumptions, and projected cost-benefit ratios used to justify planning decisions |
| 164 | Risk assessments | Risks during planning, including potential cost overruns, regulatory hurdles, or operational uncertainties, along with mitigation strategies |
| 165 | Sustainability assessments | Results of early sustainability assessments during the planning phase |
| 166 | Financing plans | Financial models, funding sources, cost breakdowns, and budget forecasts established for the project's development |
| 167 | Building description | Captures key characteristics of the planned building, including spatial configurations, structural concepts, and material choices as defined in early planning |
| 168 | Design scenario analyses | Alternative design concepts, comparative assessments, and trade-offs considered during the planning phase, providing insights for future modifications or evaluations |
| 170 | **Construction record** | Compilation of documented processes, events, and key decisions during the construction stage, providing a reference for later life cycle phases. |
| 171 | Project organization structure | Roles, responsibilities, and relationships of involved actors, including contractors, subcontractors, and project managers |
| 172 | Construction timeline and events | Chronological record of key construction milestones, delays, approvals, and site activities |
| 173 | Work progress record | Documented status reports, progress updates, and verifications of completed construction stages |

| Nr. | Data category and data points | Description |
|---|---|---|
| 174 | Testing and commissioning documentation | Records of functional tests, system verifications, and commissioning protocols ensuring compliance with technical (monitoring) requirements, e.g., of heating system installation |
| 175 | Documented changes and modifications | Logged deviations from original plans, design alterations, material substitutions, and justifications for modifications |
| 176 | Handover protocols | Formal documentation of the transition from construction to operational use, including delivered documentation and responsibilities |
| 177 | Acceptance protocols | Signed acceptance records confirming that construction meets agreed specifications, including inspections and defect lists |
| 178 | Deconstruction log / record | Special construction log / record for the end-of-life stage including deconstruction / demolition and disposal |
| 180 | **Maintenance and usage log** | Ongoing documentation of maintenance activities, renovations, and building usage over time |
| 181 | Type and scope of last renovation | Most recent renovation details, including affected areas, performed work, and materials used |
| 182 | Maintenance timeline and events | Continuously updated log of maintenance activities, repairs, and servicing, including responsible actors and dates |
| 183 | Testing and commissioning documentation | Records of inspections, functional tests, and commissioning processes related to ongoing maintenance and system upgrades |
| 184 | Building usage history | Tracked data on how the building has been used over time, including occupancy and operational changes |
| 185 | Building unit usage history | Usage records for individual units, covering tenant changes, function shifts, and operational modifications |
| 186 | Renovation roadmap(s) | Planned and ongoing renovations, including scheduling, scope, and projected impact on operations; can be the result of data analytics |
| 187 | Frequent maintenance works | Recurring maintenance tasks, scheduled servicing, and preventive measures essential for building operation |
| 190 | **Real estate management and transaction log** | Ongoing documentation of strategic decisions, transactions, and management activities related to real estate management |
| 191 | Owner-administration or external management | Management model specifying whether the building is self-managed or handled by an external service provider |
| 192 | Timeline and events of important management decisions | Chronological log of key management decisions, e.g. strategy shifts |

| Nr. | Data category and data points | Description |
|---|---|---|
| 193 | Building survey and due diligence documentation | Documentation of due diligence, including assessment scope, methods, responsible actors, purpose, information sources, and results (e.g., structural condition, compliance, legal status, financial evaluation) |
| 194 | Portfolio and asset strategy | Strategic documentation on asset positioning, investment planning, and long-term real estate portfolio development |
| 195 | Budget plans | Ongoing financial planning, including operational budgets, capital expenditure forecasts, and financial resource allocation |
| 196 | Cost-benefit analyses | Evaluations of profitability, e.g. based on return on investment (ROI), for strategic real estate decisions |
| 197 | Risk assessments | Identification and ongoing monitoring of financial, operational, legal, and market-related risks impacting real estate management |

### B.7.2 Inventory data

Table B.20:Building-related data needs in the inventory data category

| Nr. | Data category and data points | Description |
|---|---|---|
| **200** | **Inventory data** | Data on the as-built status of a building from a physical-technical perspective; includes current representations whenever possible while allowing for historical records and archived versions to track changes over time |
| **210** | **Building geometry** | Geometric representation of the building, capturing spatial structure, dimensions, and digital models as a reference for other inventory data |
| 211 | Floor plans, elevations, and sections | 2D representations of the building structure, including floor layouts, vertical sections, and external elevations |
| 212 | Area data | Floor area classifications and specifications such as gross floor area, net internal area, living space area, floor area ratio, and building footprint |
| 213 | Property and building dimensions | Key spatial measurements, including building height, number of floors (above and underground), maximum length and width, and structural grid spacing |
| 214 | Virtual building models | Digital representations of the building, including BIM models and digital twins, with spatial integration where applicable |
| 215 | Details | Architectural and geometric detailing, including façade components, material joints, and structural connections, |

| Nr. | Data category and data points | Description |
| --- | --- | --- |
| | | as well as the spatial relationships between building components and services |
| **220** | **Material and mass data** | Quantitative assessment of material volumes and mass at the whole-building level |
| 221 | Building volume calculations | Total enclosed volume of the building, including gross and net volume |
| 222 | Material quantity estimations | Aggregated material quantities at the building level, such as total concrete, steel, wood, insulation, or glazing |
| 223 | Mass distribution and structural load | Evaluations of mass distribution within the structure, total structural weight, and load-bearing considerations |
| 224 | Material life cycle and reuse potential | Overall assessment of material recoverability, recyclability, and potential reuse at the building scale |
| **230** | **Building components** | Structural and non-structural elements forming the physical building framework; includes major components (e.g., foundation, walls, roof, stairs, windows, doors) and where necessary smaller components (e.g., beams, columns, cladding, insulation, fasteners). Covers both load-bearing and non-load-bearing elements. |
| 231 | Descriptions | General description of the component, including its type and function within the building |
| 232 | Properties and attributes | Physical, mechanical, and technical characteristics such as dimensions, material composition, thermal performance, fire resistance, and acoustic properties |
| 233 | Condition monitoring and assessment | Date of installation, recorded inspections, degradation status, structural assessments, and maintenance evaluations to track the component's condition over time |
| 234 | Product documentation | Product data sheets, manufacturer details, warranty information, and compliance documents related to the component |
| 235 | Handling and maintenance instructions | Installation guidelines, maintenance procedures, repair recommendations, and end-of-life disposal or recycling instructions |
| 236 | EPDs, quality labels | EPDs and product quality labels (e.g., FSC, Cradle-to-Cradle, Blue Angel) ensuring compliance with required standards |
| 237 | Photo documentation | Visual records of the component for identification, monitoring, and documentation purposes |
| **240** | **Building services** | Technical systems and installations ensuring functionality, efficiency, and comfort in the building. Includes mechanical, electrical, plumbing (MEP), and |

| Nr. | Data category and data points | Description |
|---|---|---|
| | | automation systems, covering major installations (e.g., heating, cooling, ventilation, water supply, telecommunications, security, solar systems) and where necessary smaller components (e.g., control panels, ducts, sensors, pumps, wiring). Covers both active and passive systems. |
| 241 | Descriptions | General description of the service system or installation, including its type and function within the building |
| 242 | Properties and attributes | Technical and operational characteristics specific to building services; includes, e.g., system type, function, capacity, performance ratings, energy efficiency, flow rates, power consumption, noise levels, regulatory classifications, and integration capabilities. |
| 243 | Condition monitoring and assessment | Date of installation, recorded inspections, performance monitoring, degradation status, and maintenance evaluations to track system reliability |
| 244 | Product documentation | Product data sheets, manufacturer details, warranty information, and compliance documents related to the system |
| 245 | Handling and maintenance instructions | Installation guidelines, operational requirements, maintenance procedures, troubleshooting guidance, and end-of-life disposal or recycling instructions |
| 246 | EPDs, quality labels | EPDs and product quality labels (e.g., energy efficiency ratings) ensuring compliance with required standards |
| 247 | Photo documentation | Visual records of the system or installation for identification, monitoring, and documentation purposes |
| **250** | **Furnishing and equipment** | Movable and semi-fixed elements contributing to building usability and functionality, including furniture, appliances, office equipment, and technical devices; excludes permanently installed fixtures and fittings |
| 251 | Descriptions | General classification of the item, including type and function |
| 252 | Properties and attributes | Key characteristics such as material, dimensions, weight, energy efficiency (for appliances), or technical specifications (for equipment) |
| 253 | Condition monitoring and assessment | Date of acquisition, recorded inspections (if relevant), usage history, and replacement cycles |
| 254 | Product documentation | Manufacturer details, product data sheets, manuals, warranty, and compliance documents |
| 255 | Handling and care instructions | Maintenance, cleaning, and operational guidance (if applicable); installation details only where necessary |

| Nr. | Data category and data points | Description |
|---|---|---|
| 256 | EPDs, quality labels | EPDs, sustainability certifications (e.g., FSC for wood furniture), and compliance labels (e.g., energy efficiency ratings for appliances) |
| 257 | Photo documentation | Visual records of the item for identification, inventory management, and condition tracking |
| **260** | **Fixtures and fittings** | Permanently or semi-permanently attached elements that contribute to the building's functionality and interior fit-out; includes built-in cabinetry, sanitary installations, lighting, fixed kitchen units, built-in wardrobes, and similar elements |
| 261 | Descriptions | General classification of the item, including type and function within the building |
| 262 | Properties and attributes | Material, dimensions, surface finish, durability, fire resistance, and technical specifications where applicable |
| 263 | Condition monitoring and assessment | Date of installation, recorded inspections, wear and degradation status, and replacement needs |
| 264 | Product documentation | Manufacturer details, product data sheets, warranty information, and compliance documents |
| 265 | Handling and maintenance instructions | Cleaning, maintenance, repair, and removal/replacement guidance where applicable |
| 266 | EPDs, quality labels | Relevant sustainability and quality certifications |
| 267 | Photo documentation | Visual records for identification, monitoring, and documentation purposes |
| **270** | **Outdoor facilities** | External spaces and infrastructure contributing to site functionality and usability; includes landscaping, roads, pathways, parking, playgrounds, outdoor seating, and similar elements |
| 271 | Type and function | General classification of the facility, such as green spaces, circulation areas, recreational areas, or infrastructure elements |
| 272 | Material and durability | Key material properties, including resistance to weather, UV exposure, corrosion, wear, and permeability |
| 273 | Accessibility and usage | Information on accessibility, walkability, public vs. private use, and compliance with relevant standards (e.g., barrier-free access) |
| 274 | Condition monitoring and assessment | Regular inspections, seasonal care, repair needs, and degradation tracking |
| 275 | Maintenance and care requirements | Landscaping maintenance, cleaning, seasonal work (e.g., snow removal), and infrastructure upkeep |
| 276 | Ecological and environmental aspects | Considerations related to how outdoor facilities interact with natural and built environments; includes aspects |

| Nr. | Data category and data points | Description |
|---|---|---|
| | | such as permeability, vegetation use, microclimate effects, and landscape resilience |
| 277 | Photo documentation | Visual records for inspections, monitoring, and documentation purposes |
| **280** | **Room (book) information** | Reference data for indoor spaces, organizing functional, spatial, and usage-related aspects; serves as a structural layer connecting components, services, and equipment to specific rooms |
| 281 | Room usage and occupancy | Current and historical usage patterns; designated purpose and intensity of use |
| 282 | Number of rooms and spatial hierarchy | Total room count, grouping by function, floor, or department |
| 283 | Access and security classification | Entry permissions, restricted areas, and security considerations |
| 284 | Functional properties | Suitability of the room for its intended function, considering user needs, adaptability, environmental conditions, and technical constraints |
| 285 | Photo documentation | Visual records supporting spatial documentation and condition tracking |
| **290** | **Functional building properties** | Describes inherent building characteristics relevant to usability, adaptability, and resilience. Data can include evaluations, calculations, compliance documentation, simulations, or monitoring results, depending on the property |
| 291 | Thermal insulation and airtightness | Data on the building's ability to regulate indoor climate, including summer and winter insulation performance, airtightness, and thermal bridging effects |
| 292 | Structural integrity and resilience | Data on structural health, stability, and resistance to natural hazards such as earthquakes, storms, and floods |
| 293 | Fire and moisture protection | Data on fire resistance, compartmentation, water infiltration risks, and waterproofing measures |
| 294 | Acoustics and indoor environment | Data on sound insulation, reverberation, and overall indoor comfort, including air quality potential |
| 295 | Accessibility and space efficiency | Data on barrier-free access, circulation space, and efficient use of available building area |
| 296 | Adaptability and deconstructability | Data on the building's flexibility for future modifications, disassembly potential, and material recovery options |

### B.7.3 Economic and legal data

Table B.21:Building-related data needs in the economic and legal data category

| Nr. | Data category and data points | Description |
|---|---|---|
| **300** | **Economic and legal data** | Financial and legal information relevant to a building, including costs, revenues, property value, taxation, ownership, contracts, and approvals. |
| **310** | **Life cycle cost** | Total cost of ownership over the building's life cycle, including construction, operation, maintenance, renewal, and disposal |
| 311 | Construction costs | Costs associated with the planning, design, and construction of the building including financing costs |
| 312 | Operational costs | Recurring costs related to utilities, management, and daily operation of the building |
| 313 | Maintenance costs | Expenses for repairs, servicing, and upkeep to maintain functionality and safety |
| 314 | Renewal costs | Costs for replacing or upgrading building components as they reach the end of their service life |
| 315 | End-of-life costs | Costs related to demolition, deconstruction, material disposal, or recycling |
| 316 | $CO_2$ costs | Costs associated with emission pricing |
| **320** | **Revenues** | Income generated from building-related activities |
| 321 | Rental revenues | Income from leasing building space to tenants or other users |
| 322 | Revenues from sale of energy/electricity | Income from on-site energy production, such as solar power, cogeneration, or grid feed-in tariffs |
| 323 | Revenues from sale of used building elements | Income from reselling deconstructed materials, reusable components, or second-hand building elements |
| **330** | **Property value** | Data related to the financial valuation of a building |
| 331 | Type of value / valuation method | Specification of the valuation approach used, such as market value, cost-based valuation, or income-based valuation, including references to relevant standards or regulations |
| 332 | Input parameters and method documentation | Documentation of data used for valuation calculations and applied calculation formulas |
| 333 | Property value log | Historical records of property valuations over time, including valuation dates, assessment results, and responsible entities |

| Nr. | Data category and data points | Description |
|---|---|---|
| 334 | Value development potential | Data indicating expected value changes based on planned renovations, market forecasts, urban development plans, or regulatory changes |
| **340** | **Taxes** | Data related to tax obligations, assessments, and financial reporting for buildings |
| 341 | Property tax | Data on assessed property value for taxation, applicable tax rates, annual tax liabilities, and exemptions |
| 342 | Income tax on rental income | Taxation data related to rental revenues, including applicable deductions, exemptions, and reporting obligations |
| 343 | Value added tax | Information on VAT applied to property transactions, construction services, maintenance, and operational expenses |
| 344 | Tax depreciation | Data on depreciation rules, amortization rates, and allowances for reducing taxable income over the building’s life cycle |
| **350** | **Property rights and legal liabilities** | Data defining ownership, legal claims, and restrictions on the building, including rights of use, encumbrances, and statutory obligations |
| 351 | Ownership | Data on legal ownership structures, including owner identity, co-ownership shares, and legal entities associated with the property |
| 352 | Land register extract | Official records documenting property boundaries, ownership status, mortgages, liens, and registered rights of use |
| 353 | Cultural heritage and statutory protection | Documentation on heritage status, conservation requirements, and legal restrictions affecting modifications or demolitions |
| 354 | Easements and servitudes | Data on legally granted rights for third-party access or use of the property, such as rights-of-way, utility easements, or air rights |
| 355 | Encumbrances and liens | Information on financial or legal claims affecting the property, such as mortgages, unpaid taxes, or legal disputes |
| 356 | Legal liabilities and warranty obligations | Data on contractual and statutory liabilities, including defect liability periods, construction warranties, and compliance with legal obligations |

| Nr. | Data category and data points | Description |
|---|---|---|
| **360** | **Contracts** | Legally binding agreements related to the construction, operation, management, and financial aspects of the building |
| 361 | Construction and purchase contracts | Agreements covering the acquisition of the property, construction services, and contractor obligations |
| 362 | Financing contracts | Contracts related to loans, mortgages, and financial agreements used to fund the building's construction or operation |
| 363 | Insurance contracts | Agreements specifying coverage for property damage, liability risks, business interruption, and other building-related insurances |
| 364 | Rental contracts | Lease agreements between owners and tenants, specifying terms, obligations, and financial conditions |
| 365 | Real estate management contracts | Contracts for property management services, covering administrative, financial, and tenant-related responsibilities |
| 366 | Facility services contracts | Agreements for operational services such as cleaning, security, and maintenance |
| 367 | Contracts for other service providers | Agreements with specialized service providers, including consultants, auditors, and temporary contractors |
| **370** | **Building Permits, approvals, and compliance documents** | Legally required documents and approvals related to the construction, operation, and regulatory compliance of the building |
| 371 | Initial building permit | Official approval for the initial construction of the building, including conditions and regulatory requirements |
| 372 | Building permit modifications | Approvals for changes to the building, such as renovations, expansions, or structural alterations |
| 373 | Energy Performance Certificates (EPCs) | Legally required documents certifying a building's energy performance, efficiency class, and regulatory compliance |
| 374 | Safety compliance documents | Legally mandated reports, such as fire safety certificates and hazardous material documentation |
| 375 | Operational certifications and inspections | Documents confirming compliance with ongoing operational regulations, such as periodic building inspections, HVAC certifications, and workplace safety compliance |

### B.7.4 Performance data

Table B.22:Building-related data needs in the performance data category

| Nr. | Data category and data points | Description |
|---|---|---|
| **400** | **Performance data** | Data related to the environmental, resource, and operational performance of a building. Where applicable, data should comply with recognized standards such as DIN EN 15978 |
| **410** | **Energy performance** | Data on energy demand, consumption, generation, and import/export balances |
| 411 | Final energy demand | Total energy required for the building's operation, calculated based on theoretical or standard conditions |
| 412 | Energy consumption | Actual measured energy usage during building operation, based on metering and monitoring data |
| 413 | Generated electricity | Amount of electricity produced on-site, such as from solar panels or combined heat and power systems |
| 414 | Generated thermal energy | Amount of heat or cooling energy generated on-site, including district heating or geothermal systems |
| 415 | Imported energy | Energy supplied from external sources, such as grid electricity or district heating |
| 416 | Exported energy | Energy fed back into the grid or shared with external consumers, such as surplus solar electricity |
| **420** | **Emissions** | Data on greenhouse gas emissions and other environmental emissions associated with the building's operation and life cycle |
| 421 | Scope 1 emissions | Direct emissions from on-site energy use, such as fuel combustion for heating, backup generators, or industrial processes |
| 422 | Scope 2 emissions | Indirect emissions from purchased electricity, district heating, or cooling supplied from external sources |
| 423 | Scope 3 emissions | Other indirect emissions, specifically embodied carbon emissions from building materials, construction, and maintenance |
| 424 | Other emissions | Non-greenhouse gas emissions such as air pollutants, water discharges, or soil contamination resulting from building operation or material use |
| **430** | **Environmental impact** | Data on environmental effects related to the building's life cycle, focusing on biodiversity, climate effects, and circular economy aspects |

| Nr. | Data category and data points | Description |
|---|---|---|
| 431 | Global warming potential | Indicator for the building's contribution to climate change, typically expressed in $CO_2$-equivalent emissions over its life cycle |
| 432 | Biodiversity impact | Effects of land use, habitat destruction, or ecosystem disruption caused by the building's construction and operation |
| 433 | Circular economy metrics | Data on resource efficiency, material recovery, and reuse potential to assess the building's contribution to a circular economy |
| **440** | **Resource flows and efficiency** | Data on the consumption, reuse, and disposal of resources, including water, raw materials, and waste management |
| 441 | Net use of fresh water | Total water consumption minus recycled or reused water, capturing the impact on freshwater resources |
| 442 | Use of primary raw materials | Consumption of non-renewable and virgin raw materials used in construction and operation |
| 443 | Use of reused or recycled materials | Quantity of secondary materials integrated into the building, reducing demand for primary resources |
| 444 | Waste disposal | Data on waste generated, including classification into hazardous and non-hazardous waste streams |
| 445 | Waste recovery | Share of waste materials reused, recycled, or recovered for energy production instead of disposal |
| **450** | **Sustainability assessment log** | Data documenting sustainability assessments, methods, and certification-related records for the building |
| 451 | Type of assessment | Specification of sustainability evaluations performed, such as life cycle assessments, carbon footprint analyses, or circularity assessments |
| 452 | Input parameters and methods | Data sources, assumptions, and methodologies applied in sustainability evaluations |
| 453 | Assessment results documentation | Recorded results, scores, and performance indicators from sustainability assessments |
| 454 | Certifications and quality labels | Data on obtained certifications, rating systems, and compliance with sustainability-related requirements |
| 455 | Audit history | Chronological record of audits, inspections, and compliance checks related to sustainability performance |
| **460** | **Social and functional performance** | Data on aspects affecting user well-being, indoor environment quality, and functional adequacy of the building |
| 461 | Occupant health | Data on factors influencing health and well-being, such as air quality, lighting, and acoustic comfort |

| Nr. | Data category and data points | Description |
|---|---|---|
| 462 | Indoor environmental quality | Measurements of temperature, humidity, air exchange, and other parameters affecting indoor conditions |
| 463 | User satisfaction | Feedback and survey data on how well the building meets functional and comfort expectations |

## B.8 Principal-agent-theory: Basics

The principal-agent theory, rooted in economic theory, examines the relationship between a principal and an agent. This relationship, which manifests in various forms across economic interactions, is characterized by asymmetric information between the client (principal) and the contractor (agent). Specifically, the principal and agent possess differing levels of information prior to entering into a contractual agreement, whereby the principal commissions the agent to perform a particular task. These information asymmetries typically result in additional costs and give rise to specific characteristics and challenges within principal-agent relationships.

- First, there is the issue of “hidden characteristics” of the agent. The principal often lacks sufficient knowledge about the agent's abilities or the quality of their services or products prior to contracting. This uncertainty can lead to the selection of an unsuitable agent, a problem referred to as adverse selection.
- Second, “hidden actions” may occur after the contract has been established. In this case, the principal is unable to fully observe or evaluate the agent's actions or the quality of the outcomes. If the agent behaves opportunistically, this may result in moral hazard, whereby the agent exploits the principal’s informational disadvantage.
- Third, the phenomenon of “hold-up” describes a situation in which the principal has incurred sunk costs and becomes dependent on an agent who may act opportunistically. This dependence can limit the principal’s options and lead to inefficient outcomes (Picot et al., 2020, pp. 25–28).

Various strategies have been proposed to mitigate the negative effects associated with principal-agent problems. To address “adverse selection”, agents can engage in “signalling”, actively providing credible information about their competencies in order to reduce the principal's uncertainty. Conversely, principals may apply screening techniques, systematically gathering information to assess the agent’s suitability prior to contract formation. To prevent moral hazard, monitoring mechanisms are employed, allowing the principal to observe the agent’s actions and evaluate performance outcomes. In the case of a potential hold-up situation, measures aimed at aligning and balancing the interests of both parties are recommended to reduce dependency and opportunistic behavior (Picot et al., 2020, pp. 26–28). An overview of the key phenomena and corresponding mitigation strategies is provided in Table B.23.

Table B.23:Overview on phenomena of principal-agent theory (Picot et al., 2020, p. 28)

<table>
<tr><th></th><th colspan="3">Hidden characteristics</th><th colspan="2">Hidden action</th><th>Hidden intention</th></tr>
<tr><td>Principal's information problem</td><td colspan="3">Quality characteristics of the contract partner's performance are unknown</td><td colspan="2">Contract partner's effort is not observable or assessable</td><td>Contract partner's intentions are unknown</td></tr>
<tr><td>Cause of the problem or major influencing factor</td><td colspan="3">Concealability of characteristics</td><td colspan="2">Monitoring possibilities and costs</td><td>Resource dependence</td></tr>
<tr><td>Agent's degree of behavioral discretion</td><td colspan="3">Before contract conclusion</td><td colspan="2">After contract conclusion</td><td>After contract conclusion</td></tr>
<tr><td>Problem</td><td colspan="3">Adverse selection</td><td colspan="2">Moral hazard</td><td>Ad hoc</td></tr>
<tr><td rowspan="2">Type of problem-solving approach</td><td colspan="2">Eliminating information asymmetry through alignment of interests</td><td rowspan="2">Alignment of interests</td><td rowspan="2">Alignment of interests</td><td rowspan="2">Reducing information asymmetry (monitoring)</td><td rowspan="2">Alignment of interests</td></tr>
<tr><td>Signalling/ Screening</td><td>Self-Selection</td></tr>
</table>

# C Appendix chapter 4

## C.1 Data collection technology

Table C.1: Methods and technologies for original collection of geometric data based on Bergmeister et al. (2022) and Xie et al. (2022)

| Method | Function | ICT | Key considerations |
|---|---|---|---|
| Manual Measurement | Manual measurement of an object to capture its dimensions | None | Labor-intensive, prone to human error, and limited in precision |
| Computer-Assisted Manual Measurement | Automated measurement and data transfer into digital format | Smart devices for measurement, computers, software applications | Reduces manual effort, improves efficiency, and minimizes transcription errors |
| Photogrammetry | Data collection based on photos and videos; automated processing to create 3D models and geometric data | Camera devices, computers, software applications | Accuracy depends on lighting and environmental conditions; requires post-processing |
| Laser Scanning | Scanning of objects with lasers; high-precision modeling of complex structures and automated transfer into 3D models | Lasers, computers, software applications | Generates large datasets requiring specialized processing; high accuracy |
| LiDAR | Optical measurement of distance and velocity for 3D mapping of environments and geometric modeling | Lasers, computers, software applications | High precision and range; computationally intensive and costly |
| Tacheometry | Measurement of distance and angles for geodetic surveys and construction layout | Theodolites/total stations, computers, software applications | Requires skilled operation; suitable for high-precision angular measurements |
| Radar | Detection of subsurface structures and materials for structural assessments and material analysis | Radar devices, computers, software applications | Useful for non-destructive testing; resolution limited by material properties |

# C.2 Data storage technology

## C.2.1 Architectural patterns and storage paradigms

Table C.2: Overview on different architectural patterns for information systems based on Sunyaev (2020, pp. 36–46) and F. Auer et al. (2021, p. 1)

| Type of architecture | Underlying logic |
|---|---|
| Client-server architectures | …distribute tasks between a server, which stores and processes data, and clients, which request specific content or functionality |
| Tier architectures | …consist of multiple layers that group information system functions logically. A presentation layer manages interactions with users and external systems, an application layer processes data and runs specific applications, and a data management layer handles the storage of data in databases or file systems. |
| Peer-to-peer architectures | …mean that all participants in a network have equal capabilities and responsibilities |
| Service-oriented architecture (SOA) | …structures information systems as collections of loosely coupled, interoperable services, each providing specific business functionality. These services communicate through standardized interfaces and protocols, facilitating reusability, flexibility, and seamless integration across heterogeneous systems. Effective service coordination and governance are essential for managing complexity and ensuring reliable operations. |
| Microservices architecture | …decomposes an information system into independently deployable services, each responsible for a specific function. These services can communicate via lightweight protocols and APIs, enabling modular development, flexible scaling, and technology diversity while requiring robust orchestration and service management. |

Table C.3: Overview on data storage paradigms and how they operate based on Rahm et al. (2015, pp. 43–74)

| Storage paradigm | Underlying principle |
|---|---|
| Centralized storage | Data are stored on a single database or server, with centralized management and access control. |
| Parallel systems | Multiple interconnected servers handle data operations simultaneously, improving processing speed. |
| Distributed systems | Data are spread across multiple independent nodes, enhancing scalability and fault tolerance. |
| Federated systems | Logically integrated access to physically distributed data sources, maintaining local autonomy. |

### C.2.2 Cloud computing

Grid computing and cloud computing emerged as specialized paradigms in response to increased computing power and the growing availability of IT resources. While grid computing relies on decentralized resource control and middleware to manage standardized protocols, cloud computing is characterized by centralized resource control and management. Additionally, cloud computing introduced commercial viability through business and pricing models, making it more popular relevant in modern IT environments (Weinhardt et al., 2009, pp. 392–394).

Cloud computing deals with the availability and delivery of IT resources such as servers, storage, or software applications. These scalable IT resources are provided by a cloud provider and used on-demand remotely by the customer (Sunyaev, 2020, p. 195). Cloud computing is a paradigm for distributed IT environments, involving characteristic architectural patterns and underlying infrastructures such as data centers. These infrastructures are complemented by advancements like broadband internet, IT virtualization, containerization of applications, coordination of multi-tenant access, and servitization opportunities (Sunyaev, 2020, p. 210).

Cloud computing features several characteristics (Mell & Grance, 2011, p. 2; Sunyaev, 2020, pp. 198–199):

- Service-based IT resources: The use of cloud computing is based on service agreements. For example, customers can procure storage space or software applications through defined contracts.
- On-demand self-service: Customers can manage computing capabilities independently from the provider and adjust their usage to current needs, such as increasing server capacity during high-demand periods.
- Ubiquitous access: Cloud services are typically accessible via the internet, allowing users to connect from multiple devices through standardized communication interfaces.
- Multitenancy: Multiple customers use shared resources simultaneously while maintaining logical separation for security and privacy.
- Location independence: Customers generally do not know or control where their data are physically stored.
- Rapid elasticity: Cloud providers dynamically adjust to quick changes in demand, ensuring resources are available even during unexpected usage peaks.
- Pay-per-use billing: Pricing is based on actual usage, allowing customers to pay only for the resources consumed.

Beyond cloud customers and providers, other actors typically play roles in cloud services. Data center operators manage physical resources, certification authorities and auditors verify compliance with requirements, and cloud brokers act as intermediaries, offering customers additional services such as usage management and service integration (Sunyaev, 2020, pp. 215–217).

A popular framework for categorizing cloud services distinguishes between several models. The most basic, Infrastructure as a Service (IaaS), provides fundamental computing resources like storage and virtual machines. Customers cannot manage the infrastructure directly but control operating systems, storage, and deployed applications. Platform as a Service (PaaS) extends IaaS by allowing customers to use programming languages, libraries, and tools for designing, building, and testing applications without procuring underlying hardware. Software as a Service (SaaS) further simplifies this model by offering customers ready-to-use software applications while limiting their control to configurable settings (Mell & Grance, 2011, pp. 2–3)

Cloud service models also vary in their intended user base. Private clouds are used by specific organizations or individuals and managed by either the owner or a third party. Public clouds serve the general public, while community clouds address groups with shared requirements, such as compliance. Hybrid clouds combine aspects of private, public, or community models (Mell & Grance, 2011, p. 3). Additionally, virtual private clouds offer users isolated virtual resources accessible via Virtual Private Networks (VPN), and multi-clouds integrate services from different providers (Sunyaev, 2020, p. 207).

The flexibility offered by cloud computing has led to the decoupling of physical and virtual resources, supporting internet-based applications and driving platformization. In combination with other technologies, cloud computing has enabled disruptive business models. Some of the advantages and disadvantages of cloud computing are listed in Table C.4. While multitenancy or vendor lock-in can pose challenges, they can sometimes be mitigated, such as through multi-cloud strategies that distribute reliance across providers.

Table C.4: Advantages and disadvantages of cloud computing based on Sunyaev (2020, pp. 214–220)

| Advantages | Disadvantages |
|---|---|
| Low entry barriers | Multitenancy |
| Pay-as-you-go | Loss of control |
| Access to Leading Edge IT resources, skills and capabilities | Location intransparency |
| Quality improvements | Lack of availability |
| Cost savings | Compromised ease of use |
| Focus on core capabilities | Vendor lock-in |
| Greater flexibility and elasticity | Limited service continuity |
| Reduced time to market | Multitenancy |

Fog and edge computing are related distributed computing paradigms aimed at addressing the growing volume of data generated by devices, sensors, and applications. These approaches bring data processing closer to the point of data generation, reducing latency and improving real-time capabilities. This is particularly valuable for systems requiring immediate insights, such as IoT networks. Challenges for fog and edge computing include ensuring data security and managing the complexity of heterogeneous system environments (Sunyaev, 2020, pp. 238–255).

### C.2.3 Database technology

A database is a centrally managed data repository, made accessible via application-independent access procedures and designed to meet actor-specific information needs (Hansen et al., 2019, p. 462; Vaisman & Zimányi, 2014, p. 13). Databases form the backbone of information systems by enabling the storage, retrieval, and integration of diverse data. The development of databases was initially driven by the need for better organization of data storage and more efficient data retrieval (Domdouzis et al., 2021, p. 26).

The primary characteristics of databases include their transaction-orientation, scalability, and explicit time reference for stored or retrieved data (Hansen et al., 2019, pp. 464–465). Databases are managed through database management systems (DBMSs), which allow simultaneous access by software applications and users while ensuring data consistency, reliability, and security. These features are essential for managing the diverse and complex datasets typical of building-related information.

Over time, different database types have been developed to address specific needs (Table C.5).

Table C.5: Overview on database types, their operating principles and data premises based on (Domdouzis et al., 2021, pp. 29–42; Hansen et al., 2019, pp. 464–466; Miloslavskaya & Tolstoy, 2016, p. 302; Rahm et al., 2015, pp. 34–36)

| Database Type | Operating Principle | Data Premise |
|---|---|---|
| Hierarchical Databases | Tree-structured data storage navigated top-down | Only structured data with one-to-many relationships |
| Relational Databases (SQL) | Tabular data with Structured Query Language (SQL) queries; joins via foreign keys | Structured data with normalization requirements |
| NoSQL Databases | Flexible storage without SQL; uses Consistency, Availability, and Partition Tolerance (CAP) theorem | Unstructured or semi-structured data; high scalability |
| Document Databases | NoSQL databases storing structured documents | Interrelated, denormalized documents; suitable for metadata and internet-based data formats |
| Temporal Databases | Time-referenced data storage for lifecycle tracking | Timestamped data for historical records and transaction tracking |
| Spatial Databases | Includes positional and geometric data for GISs | Stores spatial attributes and traditional data types |
| Graph Databases | Nodes and edges representing entities and relationships | Dynamic data models without a fixed schema; suitable for complex, interconnected datasets |

| | | |
|---|---|---|
| Triple Stores | Stores RDF triples (subject, predicate, object); queried with SPARQL | Semantic relationships and metadata; useful for linked and structured datasets |
| Data Warehouses | Centralized storage for analysis and decision-making | Uniform, denormalized data optimized for querying and reporting |
| Data Lakes | Polystructured, raw data storage without strict integration | Large-scale, unstructured or semi-structured data |
| In-Memory Databases | Data stored directly in random-access memory (RAM) | Fast access but volatile storage; suitable for real-time processing |
| Historical Databases | Time-based storage to trace past records | Focuses on past states and transactional changes |
| Distributed Databases | Stores data across a network, typically close to where it is used | Data fragmented on servers; suitable for geographically dispersed systems |

Archiving data is an essential function of database systems. Many databases support archiving through features such as versioning, cold storage tiers, and backup mechanisms. Relational databases can manage historical data through temporal extensions, while NoSQL databases often facilitate long-term storage for unstructured data. Cloud-based solutions, provide cost-effective options for long-term archiving, enabling organizations to preserve large datasets while maintaining accessibility for compliance and analysis. Advanced technologies like blockchain can enhance data integrity by creating immutable records, ensuring that archived information remains trustworthy (section 4.6.4).

The growth of data amounts, often described under the umbrella of "Big Data", introduces challenges such as handling high volumes, rapid data generation (velocity), and heterogeneous data types (variety). Data lakes offer a flexible solution for storing raw, polystructured data, enabling BISs to integrate diverse datasets while minimizing upfront integration requirements (Baars & Kemper, 2021, p. 83). Similarly, hybrid database models, which combine relational and NoSQL features, are gaining traction for their ability to balance structured and unstructured data needs.

# C.3 Data sharing technology

## C.3.1 Data formats

Table C.6: Overview and evaluation of formats for sharing of building-related data based on (Borrmann, Beetz, et al., 2018; Borrmann et al., 2024; Hoitash et al., 2021; ISO/DIS 19005-4:2024-12 [draft]; Salminen, 2011)

| Format | Key characteristics | Strengths | Weaknesses | Potential use cases |
|---|---|---|---|---|
| XML | Text-based, hierarchical, schema-validated | Versatile, human- and machine-readable, interoperable | Verbose, requires schema for validation | Data exchange, system integration |
| JSON | Lightweight, text-based | Simple, fast, ideal for web-based applications | Limited support for complex data structures | Web services, APIs |
| IFC and COBie | Object-oriented, extensible | Comprehensive for BIM, supports geometry & semantics | Complex, challenges with property set standardization | BIM data exchange, life cycle integration |
| XBRL | XML-based, dual human- and machine-readable | Combines structured data with visual presentation | Specialized use cases, less flexible | Financial reporting, regulatory documents |
| PDF | Document format with metadata potential | Widely used, human-readable, legal documentation | Not machine-readable without OCR | Legal, regulatory, and archival purposes |
| PDF/A | Archival version of PDF, font-embedded, metadata-compliant | Ensures document longevity, standardized for archiving, allows digital signatures | No encryption or multimedia, not inherently machine-readable | Long-term document storage, legal records, compliance archives |
| CSV | Tabular data format, plain text | Simple, lightweight, widely supported | Lacks metadata, no hierarchical structure | Schedules, cost estimations, tables |
| RDF-based | Triples-based, semantic web-compatible | Flexible, supports reasoning and linked data | Requires specialized tools, scalability challenges | Knowledge graphs, linked datasets, semantic reasoning |

### C.3.2 Linked data and semantic web technology

LD/SW technologies rely on a set of standards that define how data can be modeled, shared, and queried in a machine-readable and interoperable way. These technologies are designed to enable decentralized, structured, and semantically rich data representation.

Key foundational components include:

- Resource Description Framework (RDF) – The core data model of LD/SW, structuring data as triples (subject, predicate, object) to establish relationships between entities
- RDF Serializations – RDF data can be stored in different formats, including:
    - Turtle (Terse RDF Triple Language) – A human-readable syntax for expressing RDF data
    - RDF/XML – An XML-based serialization of RDF
    - JSON-LD (JSON for Linked Data) – A JSON-based format that integrates RDF principles with web technologies
- Web Ontology Language (OWL) – Extends RDF with logical reasoning capabilities, allowing for the definition of ontologies that formalize domain-specific knowledge.
- RDF Schema (RDFS) – A lightweight vocabulary that adds basic schema definitions to RDF
- Shapes Constraint Language (SHACL) – Defines constraints and validation rules for RDF data structures
- Simple Knowledge Organization System (SKOS) – Designed for representing classification schemes, taxonomies, and controlled vocabularies
- SPARQL (SPARQL Protocol and RDF Query Language) – A specialized query language used to retrieve and manipulate RDF data (Böhms et al., 2023, p. 16; Pauwels et al., 2017, p. 148; Sack, 2014, p. 26)

These technologies enable semantic data integration and reasoning, making them valuable for interoperability across distributed data systems, including BISs.

### C.3.3 Building-related data standards

The following table provides a conceptual overview and preliminary analysis of selected standards for the exchange and sharing of building-related data. The assessment is not exhaustive but aims to offer a comparative view based on publicly available specifications, documentation, and reported use cases. Interoperability, semantic richness, and flexibility were assessed in an abstract manner, primarily by examining the expressiveness of the underlying data model, the number and scope of defined properties and attributes, and the range of data points covered. The evaluation reflects a relative positioning rather than strict measurement, providing an orientation for understanding different standards in the context of LC-BISs.

Table C.7: Analysis of standards for exchange and sharing of building-related data in the real estate industry

| Standard | Data Model/Format | Primary Use Case | Interoperability[1] | Semantic Richness[1] | Flexibility[1] |
|---|---|---|---|---|---|
| RealEstateCore | RDF/OWL | Smart building integration | 3 | 3 | 2 |
| BrickSchema | RDF/OWL | IoT and building systems | 3 | 3 | 3 |
| OSCRE Industry Data Model | JSON/XML | Property and facility management | 2 | 2 | 3 |
| IBPDI Global Data Model | JSON | Life cycle integration | 3 | 2 | 3 |
| RESO Data Dictionary | JSON/XML (Wiki-based) | Real estate transactions | 2 | 1 | 3 |
| OpenImmo | XML/JSON | Real estate listings | 2 | 1 | 2 |
| Society of Property Researchers | XML/JSON | Life cycle actor data exchange | 2 | 2 | 3 |
| IFC | EXPRESS/XML/JSON | BIM data exchange | 3 | 2 | 2 |
| buildingSMART Data Dictionary | RDF/XML | BIM object standardization | 2 | 2 | 3 |
| W3C Building Topology Ontology (BOT) | RDF/OWL | Geometry representation in BIM | 3 | 3 | 3 |
| RealEstateCore Ontology | RDF/OWL | Knowledge graph for buildings | 3 | 3 | 3 |
| Brick Consortium Schema | RDF/OWL | Building system classification | 3 | 3 | 2 |

[1] Legend: 1 (low), 2 (moderate), 3 (high)

Table C.8: Overview on committee-driven standards for data exchange and sharing in the real estate industry

| Standard | Focus | Purpose | Relevance to BISs |
|---|---|---|---|
| DIN EN ISO 12006-2:2020-07 | Construction-related classification | Framework for organizing information | Basis for taxonomies and ontologies. |
| DIN EN ISO 16739-1:2021-11 | IFC schema and data architecture | Standardizing BIM data representation | Key for BIM interoperability. |
| DIN EN 17632-1:2023-04 | Linked data and semantic web in BIM | Integrating semantic web technologies | Supports advanced reasoning and interoperability. |
| DIN EN ISO 19650-1 | BIM information management | Guidelines for BIM workflows | Life cycle data management. |
| DIN EN ISO 21597-1:2021-07 | Exchange of heterogeneous data | Data exchange schema | Supports multi-source data integration. |
| DIN EN ISO 29481-1:2025-01 [draft] | Information Delivery Manuals (IDM) | Guidance on actor constellations | Enables coordinated data exchanges. |

## C.3.4 Application programming interfaces

An Application Programming Interface (API) is a set of rules and protocols that allows software applications to communicate and exchange data. APIs define how one system can request data or services from another and how responses are structured.

Key Characteristics of APIs:

- Standardized communication – APIs enable systems to interact using predefined request and response formats.
- Automation & integration – They allow applications to exchange data without manual input, enabling process automation.
- Modular & scalable – APIs make it possible to connect different systems without modifying their core functionality.

APIs are widely used in web-based applications and digital platforms. They play a key role in data sharing and system integration by allowing applications to retrieve, send, and update information efficiently.

A commonly used type is the REST or RESTful API (Representational State Transfer), which operates over the web using standard HTTP methods such as GET, POST, PUT, and DELETE. REST APIs are particularly suitable for modular, scalable system architectures and are widely adopted due to their simplicity, statelessness, and support for structured data exchange, typically in JSON format (Richardson & Amundsen, 2013).

# C.4 Basics of data quality

Understanding what constitutes data quality is fundamental for effective management of building-related information. There is no universal definition, but data quality generally refers to the ability of data to meet the specific needs of actors. High-quality data ensures that actors can trust and use the information to make informed decisions, execute tasks efficiently, and avoid costly errors. Data quality dimensions provide a structured way to describe and assess data quality. In academic literature, these dimensions are often defined as attributes that describe the quality of data in specific contexts, offering a basis for identifying and addressing data-related challenges (Rohweder et al., 2021, p. 24).

The importance of these dimensions becomes apparent when considering common problems in the real estate industry, such as missing or inaccessible data, false or inconsistent data, and redundant or incompatible datasets. Each of these issues can be linked to specific dimensions. For example, missing data highlights the need for completeness, while false data relates to accuracy and consistency. These dimensions offer a framework for addressing such challenges systematically.

Several models exist to categorize data quality dimensions. One prominent approach, based on an empirical study of IT users, identifies 15 dimensions of data quality that summarize the most critical attributes. These dimensions can be grouped into four categories (Figure C.1):

- System-supported dimensions: Attributes linked to the environment in which data are processed or used.
- Inherent dimensions: Characteristics of the data itself, such as accuracy and objectivity.
- Representation-related dimensions: How data are presented, focusing on comprehensibility and conciseness.
- Purpose-related dimensions: Context-specific attributes that determine whether data are fit for a particular purpose (Rohweder et al., 2021, pp. 26–29).

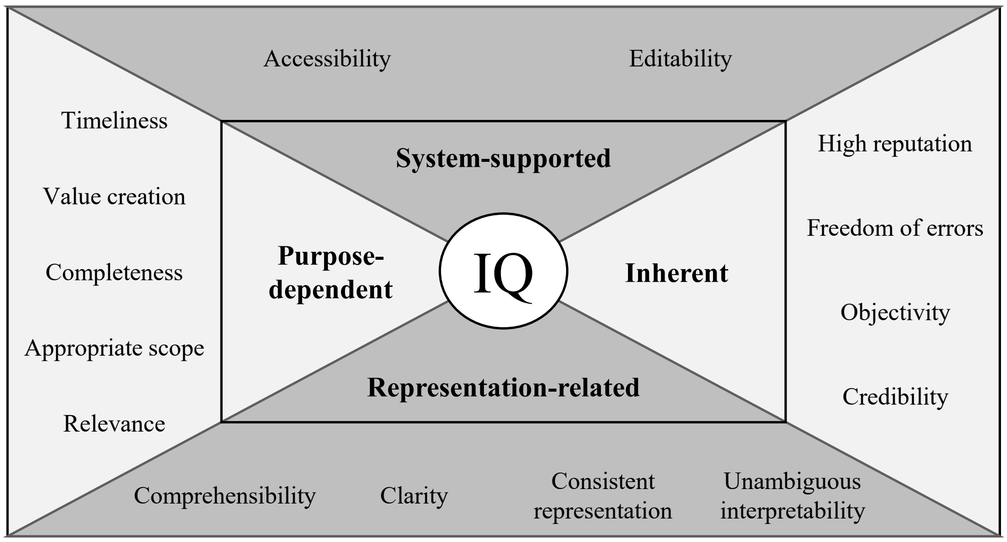



Figure C.1: 15 dimensions of information quality based on Rohweder et al. (2021, p. 28)

A complementary approach by Batini and Scannapieco (2016, p. 23) categorizes dimensions into eight clusters (Table C.9). This model has the advantage of flexibility, allowing additional attributes to be aggregated under existing clusters. Both approaches underscore the complexity and specificity of data quality management, offering robust tools for assessing building-related data.

Table C.9: Data quality clusters (Batini & Scannapieco, 2016, p. 23)

| Cluster | Data Quality Dimensions | Explanation |
|---|---|---|
| Cluster 1 | Accuracy, Correctness, Validity, Precision | Focus on the adherence to a given reality of interest. |
| Cluster 2 | Completeness, Pertinence, Relevance | Capability of representing all and only the relevant aspects of the reality of interest. |
| Cluster 3 | Redundancy, Minimality, Compactness, Conciseness | Capability of representing the aspects of the reality of interest with minimal information use. |
| Cluster 4 | Readability, Comprehensibility, Clarity, Simplicity | Ease of understanding and use of information by users. |
| Cluster 5 | Accessibility, Availability | Ability of users to access information based on their culture, physical status, and available technologies. |
| Cluster 6 | Consistency, Cohesion, Coherence | Capability of information to comply without contradictions with all properties of the reality of interest, considering integrity constraints, data edits, business rules, etc. |
| Cluster 7 | Usefulness | Related to the advantage the user gains from using the information. |
| Cluster 8 | Trust (Believability, Reliability, Reputation) | Captures how much the information derives from an authoritative source, also covering security issues. |

While these dimensions provide a theoretical foundation, their practical application requires further refinement. Data quality dimensions must be defined and operationalized for different types of data to ensure their relevance and effectiveness in specific contexts. Such operationalization enables actors to establish measurable standards and tailored strategies for maintaining data quality throughout the building life cycle.

A modern framework for setting data quality requirements is the FAIR principles (Findable, Accessible, Interoperable, Reusable). These principles were originally developed to improve data management in scientific research but are increasingly applied to other fields, including building-related information management. They emphasize that data should be:

- Findable: Data must have unique and persistent identifiers, such as DOIs, and include rich metadata to ensure discoverability.

- Accessible: Data should be retrievable through well-defined protocols, even with appropriate access restrictions.
- Interoperable: Data must use standardized formats and vocabularies to ensure compatibility and integration across systems, which is particularly critical in BIS contexts.
- Reusable: Data should be described clearly and provided with sufficient metadata to support reuse in various contexts, ensuring long-term value (Jacobsen et al., 2020, pp. 11–14).

Beyond the frameworks discussed, data quality is also addressed in international standardization efforts, particularly within the ISO 8000 series. This set of standards provides specifications on data quality principles, governance, management, and assessment, with a specific focus on the exchange of master data in business environments. However, due to access restrictions, the ISO 8000 standards could not be directly consulted in the preparation of this thesis.

# C.5 Data analytics technology

## C.5.1 Relevant technologies

The wide range of methods, principles, algorithms, models, technologies, and processes used to analyze digital data, and often to generate new data in the process, can be challenging to differentiate. Definitions vary depending on the specific scientific field or context, and practical interpretations of these concepts often diverge. To provide a clearer overview, Table C.10 highlights key terms associated with data analytics and illustrates some of the overlaps between them. This selection is not exhaustive, reflecting the fast-paced and evolving nature of ICT.

Table C.10:Relevant technologies in the context of data analytics

| Technology | Description |
|---|---|
| Data Science | An interdisciplinary academic field and professional discipline which deals with methods and systems to extract knowledge from data and to apply it in various application domains; makes use of AI, ML, statistics and other quantitative fields (Haneke et al., 2021, p. 8; Kotu & Deshpande, 2019, p. 4; Papp et al., 2022, p. 3) |
| Computer Science | Refers to the study of computers and computational systems using correspondent theoretical and practical disciplines while using hardware and software (Michigan tech, 2023) |
| (Big) Data Analytics | Data Analytics stands for the analysis of data via computer systems to support decisions; makes use of many disciplines and methods (Runkler, 2020, p. 2); special techniques and applications to answer the requirements of big data |
| Data Mining | Another term for statistical and algorithmic analyzing of data and drawing insights from it (Runkler, 2020, p. 2); special forms like text mining exist depending on the type of data |

| | |
|---|---|
| Business Intelligence and Analytics (BIA) | Refers to the processing and analysis of data in businesses to draw insights of them and support decision-making; also covers the information system environment, implemented techniques and connectios to data storage and distribution (Baars & Kemper, 2021, p. 8) |
| Artificial Intelligence (AI) | Stands for the simulation of human intelligence through machines can be found in more and more application domains (Papp et al., 2022, p. 8), especially in automation and robotics |
| Machine Learning (ML) | A field of algorithmic learning from data and creating of new data by predicting the environment and behavior of objects (Langs et al., 2022, p. 237) |
| Computer Vision | Analysis of image data and transformation into other forms of data based on specific techniques and algorithms by simulating the human visual system (Licandro, 2022, pp. 317–318) |
| Data Visualization and Visual Analytics | Data Visualization uses the advantages of visualized data for analytical reasons (Vesela, 2022, p. 385); Visual Analytics describes the actual process of analyzing visualized data |

The diversity of methods and technologies for data analysis reflects the rapid evolution of ICT and its increasing relevance across industries. While terms like data mining, AI, ML, and computer vision often overlap in practice, they contribute unique capabilities to analyzing and interpreting data. For example, data mining emphasizes identifying patterns in large datasets using methods such as clustering, classification, and time-series analysis, with applications ranging from structured data to more complex types like time-series or graph data (Aggarwal, 2015, pp. 6–19; Baars & Kemper, 2021, pp. 128–129). AI builds on such processes to simulate human-like intelligence in data interpretation and decision-making, enabling advancements in automation and predictive analytics. Its abilities include processing natural language, recognizing images, planning sequences of actions, and learning from past experiences to optimize future behavior (Chowdhary, 2020, pp. 10–13).

A core component of AI, ML, employs algorithms to learn from historical data and generate models capable of making predictions about new scenarios. Techniques like supervised learning, unsupervised learning, and reinforcement learning enable a wide range of applications, from dynamic classification tasks to real-time decision-making. In addition, advanced ML approaches like neural networks and deep learning allow for more complex analysis, such as extracting patterns from images using convolutional neural networks (CNNs) or detecting anomalies in large datasets (Langs et al., 2022, pp. 218–224).

Computer vision, closely tied to ML, processes and analyzes image data to transform it into actionable insights. By replicating human vision, it enables tasks like detecting structural inconsistencies or creating 3D models, increasingly supported by ML algorithms (Licandro, 2022, pp. 317–318). Together, these technologies form the foundation of modern data analytics, with applications continuously expanding as ICT evolves.

### C.5.2 Types of data analytics

Data analytics can be categorized into four main types: descriptive, diagnostic, predictive, and prescriptive analytics. Each type serves a distinct purpose in extracting insights, supporting decision-making, and optimizing processes.

- Descriptive Analytics focuses on summarizing historical and real-time data to provide an overview of current conditions. This includes reports, dashboards, and visualizations that display key metrics, such as trends in resource consumption or system performance. While descriptive analytics does not explain why certain patterns occur, it establishes the foundation for further analysis.
- Diagnostic Analytics goes beyond description by identifying causal relationships and uncovering the reasons behind observed trends or anomalies. For example, it can analyze sensor data to determine why fluctuations occur in a system's operation, helping to pinpoint inefficiencies or failures.
- Predictive Analytics uses historical data and statistical models to forecast future conditions. This is particularly useful for anticipating equipment failures, estimating demand patterns, or identifying trends that could affect system performance. Machine learning models often enhance predictive analytics by recognizing patterns and making probabilistic forecasts.
- Prescriptive Analytics extends predictive insights by suggesting optimal actions to improve performance or prevent undesired outcomes. This may involve AI-driven recommendations, automated scheduling, or optimization algorithms that enhance efficiency and decision-making. Prescriptive analytics integrates techniques such as machine learning, simulation, and decision-support models to provide actionable guidance (Cote, 2021).

Each of these analytics types plays a role in data-driven decision-making, with effectiveness depending on data quality, system interoperability, and computational capabilities. Their application varies across industries, but they collectively form the foundation for modern data-driven optimization and automation.

### C.5.3 Data analytics throughout the life cycle

Table C.11:Use cases for data analytics in the development and construction stage

| Task area | Use case | Role of data analytics | Evidence |
|---|---|---|---|
| Planning and Feasibility | Automated property analysis and feasibility studies | Integrates geospatial, economic, and regulatory data to streamline site selection and evaluate project viability. | Rudolph (2022, p. 130) |
| | Automated market and location analysis | Predicts optimal locations using ML models based on investor requirements and market trends. | Nern (2021) |
| | Design optimization | Generates and evaluates design options using deep learning, improving planning efficiency. | Baduge et al. (2022, p. 7) |
| | Early-stage economic appraisals | Analyzes project cost and revenue potential using dynamic modeling approaches. | Abioye et al. (2021, p. 6) |
| Project Management | Dynamic cost and schedule predictions | Provides real-time forecasts to optimize resource allocation and reduce delays. | Rampini and Cecconi (2022, p. 900) |
| | Contractor selection | Identifies suitable contractors using algorithms based on task requirements and conditions. | Baduge et al. (2022, p. 14) |
| Site Monitoring and Safety | Site monitoring and optimization | Tracks resources, monitors safety, and ensures compliance through IoT and image recognition technologies. | Abioye et al. (2021, p. 6) |
| | Wearable technology for worker safety | Uses sensor data from wearable devices to monitor and enhance worker safety on-site. | Abioye et al. (2021, pp. 7–8) |
| | Waste generation analysis | Identifies and categorizes construction waste profiles using CNNs to improve sustainability practices. | Abioye et al. (2021, p. 5) |
| Compliance and Quality | Automated compliance reviews with construction codes | Uses NLP and ML to check designs and processes against location-specific regulations, including fire protection and structural safety. | Bilal et al. (2016, p. 508), Rampini and Cecconi (2022, p. 899) |
| | Predictive analytics for material selection | Evaluates materials based on performance and sustainability criteria using ML algorithms. | Baduge et al. (2022, p. 10) |

Table C.12:Use cases for data analytics in the use stage

| Use case | Role of data analytics | Sources |
|---|---|---|
| Predictive maintenance | Forecasts potential failures in building systems and components, enabling proactive interventions. | Rampini and Cecconi (2022, p. 898), Araszkiewicz (2017, p. 1039) |
| Dynamic energy management | Optimizes heating, cooling, and lighting systems in real time based on occupant behavior and weather data. | Abioye et al. (2021, p. 8) |
| Automated post-occupancy evaluation | Analyzes usage data and occupant feedback to improve building performance and satisfaction. | Rampini and Cecconi (2022, p. 896) |
| Retrofit planning | Aggregates monitoring data to prioritize and coordinate energy efficiency measures. | Rampini and Cecconi (2022, p. 896) |
| Energy consumption prediction | Estimates energy demand using historical and real-time data to support operational planning. | Baduge et al. (2022, p. 16), (Rampini & Cecconi, 2022, p. 894) |
| Structural health supervision | Monitors building components for signs of wear or damage, ensuring timely repairs and safety compliance. | Araszkiewicz (2017, p. 1039) |
| Occupant safety monitoring | Uses data from sensors and predictive models to enhance security and detect risks. | Baduge et al. (2022, p. 17) |
| Automated property valuation with AVMs | Estimates property value using data-driven models that integrate real estate data, building characteristics, and external factors such as location or market trends. | Su et al. (2021) |

# C.6 Data security technology

## C.6.1 Basics of data and information security

Information security as the more general term for data security “refers to the policies, procedures, and technical measures used to prevent unauthorized access, alteration, theft, or physical damage to information systems” (Laudon & Laudon, 2014, p. 325). Moreover, other terms such as IT security or cyber security closely related to information security and often address overlapping aspects (Eckert, 2018, p. 1; Kappes, 2022, p. 2).

Information security follows goals like the confidentiality, integrity, and availability of information (DIN EN ISO/IEC 27000:2020-06, p. 11). According to Kappes (2022, p. 3), these goals form the three main aspects of information security, which is also referred to as CIA triad, while Hansen et al. (2019, p. 386) also account “authentication” as one of the basic goals (Table C.13). This foundation is particularly relevant for BISs, where maintaining secure data throughout the life cycle of a building is critical for enabling trust, collaboration, and effective decision-making across multiple actors.

Table C.13:Objectives of data and information security based on (DIN EN ISO/IEC 27000:2020-06, pp. 7–14; Hansen et al., 2019, pp. 391–392; Kappes, 2022, p. 3)

| Category | Goal | Explanation |
|---|---|---|
| Basic goals | Confidentiality | Limitation of access to specific information |
| | Data integrity | Completeness, originality, and accuracy of data |
| | Authentication | Unambiguous identification of an entity by checking the conformation of stated properties |
| | Availability | Property of an entity of being accessible and usable when needed |
| Higher goals | Data authencity | Veryfiable identification of data |
| | Non-repudiation | Verification of an event and involved entities |
| | Access control | Measures to ensure that the access to an information system is authorized |
| | Accountability | Protocol of which users accessed which information resources |

Hansen et al. (2019, p. 383) see data security as one of three tasks in information security in addition to identity security and communication security. Data security sits at the bottom of these three tasks, primarily concerning the security of data stored within networks. Communication security refers to the security of the network and connected communication pathways. Identity security addresses the identification, authentication and authorization of users (Hansen et al., 2019, p. 384).

One aspect that is often mentioned alongside data security is data privacy and the protection of data privacy. While data security focuses on protecting data from unauthorized access and alteration, data privacy emphasizes the responsible use of personal data in compliance with legal and ethical standards. In general, data privacy counts as a basic condition for individual freedom and self-determination. The increasing digitalization and widespread use of web-based applications have amplified the challenge of ensuring data privacy, making it a critical consideration for organizations and BISs alike.

## C.6.2 Basics of access controlling in information systems

The increased use of digital platforms where several parties read and edit data emphasizes the relevance of access control as a key measure of data security. This is particularly crucial for BISs, where multiple actors interact with shared data throughout all lifecycle stages. Effective access control ensures that actors can fulfill their tasks while maintaining data security, integrity, and confidentiality. Additionally, it supports trust among stakeholders by preventing unauthorized access and misuse.

Access control is typically a part of a broader Identity and Access Management (IAM) framework, which provides a structured approach to managing user identities, roles, and access rights in information systems. IAM frameworks help ensure that only authorized users can access sensitive data and resources while maintaining compliance with organizational policies and regulations (Osmanoglu, 2014, pp. 47–49).

The literature defines security models to describe access controlling mechanisms. Security models consist of subjects (users of a system) and objects (generally pieces of information or resources). Access control rights determine whether an information flow can be established between a subject and an object. Those rights can be either universal or object-specific. Moreover, simple and complex access constraints can limit the access in more detail. According to Eckert (2018, p. 242), the controlling of access rights is one of two possible security strategies, the information flow strategy being the other one. Several options exist for the access controlling strategy:

- Discretionary access control (DAC) strategies build on the assumption that the data owner is solely responsible for protecting the data. The data owner can decide for themselves to whom they grant access. The advantage of this model is its flexibility and the personal responsibility. However, due to the high manual effort, it is only suitable for small user groups (Eckert, 2018, pp. 242–243; Hansen et al., 2019, p. 421).
- Mandatory access control (MAC) strategies use a rule-based approach for defining access control rights. For every pair of subject and object, it must be decided if an information flow is permitted. The advantages and downsides of this strategy are similar to the ones of DAC strategies (Eckert, 2018, p. 243; Hansen et al., 2019, p. 421).
- Role-based access control (RBAC) strategies differ to the point that access rights are not given to subjects, but to predefined roles. Here, the focus lies rather on the tasks than on the subjects and objects. Subjects are allocated to roles depending on their information needs and the preferences of the data owner (Eckert, 2018, p. 243; Hansen et al., 2019, p. 422).
- Attribute-based access control (ABAC) strategies, also called policy-based access control (PBAC), use policies for access decisions. Policies in the form of rules, constraints etc. are applied considering various attributes and their values regarding the subject, environment, or resource/object, for example (Hu, 2018, p. 14).

RBAC offers significant potential for structured, task-oriented environments whereas ABAC, on the other hand, excels in environments where flexibility and real-time decision-making are required.

### C.6.3 Data classification and data sensitivity

Table C.14:Example for a data classification (ISO/IEC TS 38505-3:2021-12, p. 14)

| Classification | Description |
|---|---|
| Highly sensitive | Most restricted data, requiring the greatest care. Disclosure could cause significant harm to the organization, customers, or individuals. |
| Sensitive | Restricted data requiring protection. Disclosure could cause harm to the organization, customers, or individuals. |
| Internal | Data retained within the organization but not classified as sensitive. |
| Default | All other data assets where access poses no potential harm to the organization or its stakeholders. |

### C.6.4 Threats on data security

There are numerous threats on the security of data and information systems that can lead to severe technical, economic and personal damages. Some threats originate from the natural and man-made environment of an information system. Natural hazards, such as floods, fires, or earthquakes for example can damage physical infrastructures, including data centers. Similarly, technical threats, such as system malfunctions, software vulnerabilities, or internet failures, often result from errors during system design, implementation, or administration (Kappes, 2022, p. 7). Organizational threats refer to aspects that derive from human behavior or insufficiencies in security management. Organizational risks arise from human behavior or insufficient security protocols, such as unauthorized access, accidental data alterations, or improper disposal of sensitive hardware (Hansen et al., 2019, p. 415).

Cyber-related threats are increasingly prevalent and sophisticated. Passive attacks, such as eavesdropping or data interception, pose risks by covertly gathering sensitive information. In contrast, active attacks, such as phishing or denial-of-service (DoS) attacks, involve direct manipulation or disruption of systems (Kappes, 2022, p. 6). Malware, including viruses, worms, ransomware, and trojans, remains a significant threat, often infiltrating systems without user knowledge and causing disruptions to software and hardware (Hansen et al., 2019, p. 417; Kappes, 2022, pp. 115–116; Laudon & Laudon, 2014, pp. 328–330).

Emerging technologies also introduce new risks. AI-generated phishing attacks demonstrate how machine learning can exploit human vulnerabilities (S. Kumar et al., 2024, p. 218), while supply chain attacks target third-party software or services (Andreoli et al., 2023, p. 1). Although quantum computing remains a future threat, its potential to undermine current encryption methods highlights the need for proactive security planning (Yalcin et al., 2024, p. 1).

The impacts of security threats are severe. A successful attack could lead to operational disruptions, resulting in financial losses and reputational damage. Breaches of sensitive data could lead to regulatory penalties under laws like the GDPR. A summary of key threats is provided in Table C.15.

Table C.15: Threats on data security and their potential impact on building information systems based on (Eckert, 2018; Hansen et al., 2019; Kappes, 2022; Laudon & Laudon, 2014)

| Category | Description | Examples |
|---|---|---|
| Malicious Software | Unauthorized programs that disrupt systems or steal data. | Ransomware, trojans, spyware, SQL injection. |
| Hacking | Unauthorized access to systems for exploitation or control. | Phishing, DoS attacks, identity theft, zero-day exploits. |
| Organizational Threats | Human error or insufficient security protocols. | Unauthorized access, accidental data deletion, poor disposal of hardware. |
| Technical Threats | Issues arising from design or operation of ICT systems. | System malfunctions, software bugs, outdated firmware. |
| Environmental Threats | Natural or external factors impacting infrastructure. | Floods, fires, power outages. |
| Emerging Threats | New risks from advanced technologies or supply chain dependencies. | AI-generated phishing, supply chain attacks, quantum computing risks. |

Additional to the described threats on data security in general, there are threats that specifically affect data privacy. These threats often derive from the activity of individuals on the internet. Providers of websites and web applications use cookies and other tracking methods to collect data of users. The main goal of this is to gain new customers or to lock-in existing customers by reacting to customer needs. This sensitive data can easily be used to create personal profiles, especially from search engine providers. As a result, there is the risk that these data are abused or the target of an attack. Also in the corporate context, data privacy plays an important role. Employers are responsible to protect personal data that is stored in personal information systems and need to comply with existing laws that protect employers from forbidden tracking activities (Hansen et al., 2019, pp. 427–428).

Depending on the architecture and the environment of an information system, more specific threats can exist. For example, web applications need to take care of the security of clients, the backend, the data exchange and the application itself. Clients might face errors in the visualization of objects in the browser. They also might be threatened by downloads containing malware by accidentially accessing fake servers. Backend security might be threatened through malware, bad programming or poor internet connections (Kappes, 2022, pp. 348–349). Another special case concerns the security in cloud environments. Security issues include the security of the application system, the network conncetion and the host system (Kappes, 2022, p. 375). Specifying on data, which can be in states of rest, transit and use, different types of threats can occur in cloud environments (Table C.16). For example, when data are at rest, data persistence must be ensured by the cloud provider including that data are deleted once it is not needed anymore (Vimal Kumar et al., 2017, p. 10).

Table C.16:Data security issues for different states of the data based on Vimal Kumar et al. (2017, p. 9)

| State of data | Data security issues |
|---|---|
| Data-at-rest | Data persistence, access control, cloud service provider accountability, secure data sharing |
| Data-in-use | Source computation, machine isolation, verifiable computing |
| Data-in-transit | Data relocation, perimeter security, data outsourcing |
| Cross-cutting issues | Information leakage, data provenance & logging, governance, risk management and compliance |

In addition to the general threats to data security, threats specific to data privacy warrant particular attention. These threats often stem from the activities of individuals or organizations on the internet. For example, providers of websites and web applications frequently use cookies and tracking methods to collect user data, aiming to enhance customer targeting or lock-in existing clients. While such practices may offer benefits for businesses, they also expose sensitive data to misuse or attacks, especially when combined into personal profiles by search engine providers or other platforms (Hansen et al., 2019, pp. 427–428).

Web applications, commonly used for accessing and managing building-related data, must ensure the security of client interactions, backend operations, and data exchanges. Potential vulnerabilities include errors in browser-based visualizations, downloads containing malware from fake servers, and backend threats arising from poor programming or unreliable internet connections (Kappes, 2022, pp. 348–349). Such risks highlight the critical importance of secure application design and maintenance in BISs.

### C.6.5 Basics of measures for data security

In order to pursue data security, organizations usually implement some form of security management. One way to meet the needs of security management is to install an information security management system (ISMS). An ISMS includes policies, guidelines, measures and connected resources to protect information resources (DIN EN ISO/IEC 27000:2020-06, p. 21). Measures to ensure information security are also referred to as controls in the scientific literature and in standardization (DIN EN ISO/IEC 27000:2020-06, p. 9; Laudon & Laudon, 2014, p. 325).

The goal regarding security in the development and usage of information systems is to minimize the risks of facing threats and the resulting damages. To achieve this, possible threats must be identified first, and their risk must be evaluated (Laudon & Laudon, 2014, p. 341). Subsequently, a tailored set of security measures must be implemented to fit the specific requirements of an information system and its actors. In standardization, four categories of measures for information security are defined: organizational, personal, physical, and technological measures (Table C.17).

Table C.17:Types of data security measures and examples based on (DIN EN ISO /IEC 27001:2017-06; DIN EN ISO /IEC 27002:2024-01)

| Category | Examples |
|---|---|
| Organizational measures | Security roles, guidelines, access control rights, identity management, policies for security issues, protection of data privacy |
| Personal measures | Security checks, employee training, process of moderation, confidentiality and non-disclosure agreements |
| Physical measures | Security barriers, protection against natural hazards, protection of ICT infrastructure, secure disposal of ICT |
| Technological measures | Access rights and limitation, authentication, protection against malware, network security, cryptography, secure coding, logging |

To choose appropriate security measures, the primary security goal being pursued should be clear. For instance, cryptographic methods support the integrity and confidentiality of data. Cryptography involves encrypting and decrypting messages so they remain secret. Specific encryption keys transform data into numerical codes that can only be decrypted with the correct key (Hansen et al., 2019, p. 397; Laudon & Laudon, 2014, p. 349).

Authentication of users is another critical measure. Common methods include passwords, chip cards, and biometric authentication. Multifactor authentication and identity management systems can further enhance the security of access to shared information system resources. Table C.18 provides examples of measures aligned with key security goals.

Table C.18:Measures to pursue different data security goals

| Security goal | Examples for measures |
|---|---|
| Integrity, confidentiality and non-repudiation | Private key encryption, public key encryption, cryptographic hash functions, steganography, virtual private networks (VPNs) (Hansen et al., 2019, pp. 398–399; Laudon & Laudon, 2014, pp. 349–350) |
| Authentication | Passwords, transaction authentication numbers (TANs), chip cards, digital signatures, biometric authentication, identity management, VPNs (Hansen et al., 2019, pp. 394–396; Kappes, 2022, pp. 51–68; Laudon & Laudon, 2014, pp. 345–346) |
| Availability | Fault-tolerant computer systems, high-availability computing, recovery-oriented computing (Laudon & Laudon, 2014, pp. 350–351) |

Against the background of threats from malware and cyberattacks, additional preventive measures are necessary (Kappes, 2022, pp. 121–124; Laudon & Laudon, 2014, pp. 347–348). Examples include:

- The use of antivirus software and intrusion detection systems.
- Regular updating of software and operating systems to close vulnerabilities.
- Firewalls and filters to control network traffic.

- Real-time anomaly detection to validate and secure sensor-generated data.

Cloud computing presents unique security challenges. Clients must ensure that cloud providers comply with relevant jurisdictions and implement robust security protocols. Service-level agreements (SLAs) should outline data persistence policies, deletion practices, and measures for handling data breaches (Laudon & Laudon, 2014, p. 353). Transparency features, such as data provenance tracking, are also crucial to establish trust in cloud environments (Vimal Kumar et al., 2017, pp. 6–7).

### C.6.6 Basics of blockchain technology

Essentially, blockchain technology is a concept to store data in a database. A blockchain constitutes a type of distributed database in which the data entries are immutable. The data entries are called blocks (records), which are consecutively added to the chain of already existing blocks. The blocks of a blockchain are connected through the method of hashing, which means that every block contains a cryptographic hash function of its predecessor. In addition, each block typically includes a timestamp, details of the transaction, and metadata about involved actors, ensuring transparency and traceability (Hansen et al., 2019, pp. 406–408). A blockchain is also called distributed ledger. This means that a blockchain is stored redundantly and in identical form at different physical locations in a distributed network. The characteristic of such a distributed network is that the breakdown of one node does not affect the function of such a system (Jedelsky, 2022, p. 475). In practice, there are different forms of blockchains: Public blockchains have in common that there is no restriction on who can access the blockchain. Private blockchains on the other hand use some form of access control. Hybrid blockchains use features of both types of blockchains.

The typical process to store a block in a blockchain consists of the following steps:

- Create, sign, and distribute a transaction: One participant creates a transaction, which must be confirmed by others before it can be added to a block.
- Collect transactions in a block and calculate a hash function for the block: Participants “mine” blocks by calculating hash functions for the transactions and the block as a whole.
- Link the block to the last block in the blockchain: A block is linked by embedding the hash value of the previous block into its header (Figure C.2).
- Publish the block based on a consensus method: Blocks are permanently added to the blockchain, often through methods like “proof of work” or “proof of stake,” depending on the system.
- Reward participants: In some systems, participants who successfully add blocks are rewarded (Eckert, 2018, pp. 829–834).

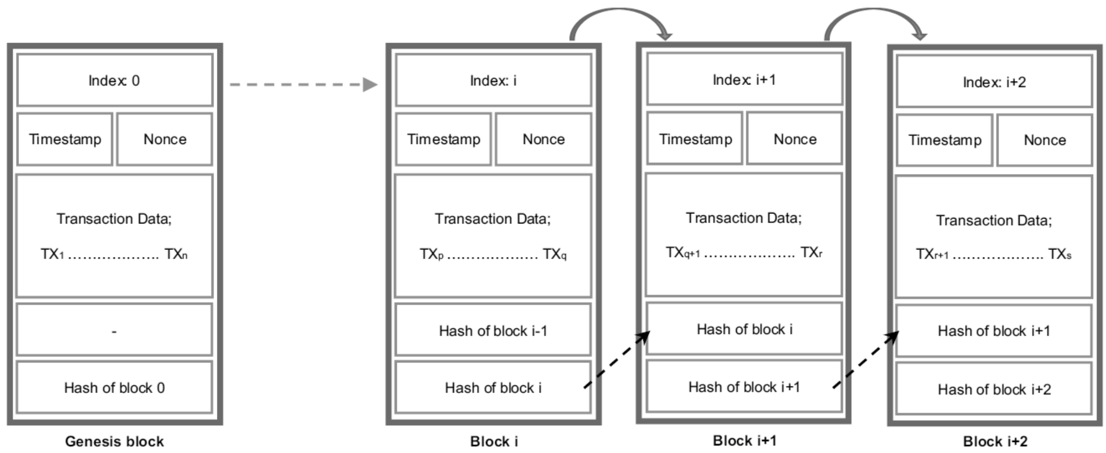



Figure C.2: Example of a blockchain (Perera et al., 2020, p. 4)

Blockchain technology shows some interesting features which can lead to specific advantages over other database types:

- Immutability: Once stored in a blockchain, transactions are unchangeable, making it secure against manipulation.
- Transparency: All participants can trace transactions, fostering trust and accountability.
- Decentralization: A blockchain does not require a centralized authority, reducing dependence on third parties.
- Resilience: Peer-to-peer networks ensure that the failure of a single node does not compromise the system's functionality (Eckert, 2018, p. 827; Hansen et al., 2019, p. 409).

Due to its characteristic features, blockchain technology fulfills several data security goals by default. The integrity of data is maintained through cryptographic hash functions. Blockchains also meet requirements for availability, authenticity, non-repudiation, and accountability. However, confidentiality is not inherently ensured by blockchains, as their primary focus lies on transparency. For BISs, this limitation can be addressed by combining blockchain with encryption for sensitive data.

In addition to conventional security threats, users of blockchains face specific risks. For example, if a single participant controls more than 50 percent of the network's computing power, it could lead to manipulation of the blockchain (a "51 % attack"). Similarly, mining pools, where participants collaborate to mine blocks, can concentrate control and pose risks (Eckert, 2018, pp. 838–841). Energy consumption, particularly in proof-of-work systems, and scalability limitations are additional challenges that need to be addressed before widespread adoption.

# D Appendix chapter 5

## D.1 Examples for metadata

Table D.1: Overview on potentially relevant metadata points in life cycle building information systems

| Metadata type | Example elements | Purpose / description |
|---|---|---|
| Descriptive | Title, object type (building, unit, room), classification codes, tags | Clarifies what the data are about and to which object it refers |
| Administrative | Version ID, creation/modification date, data status (as-designed, as-built), responsible party | Enables governance, compliance, and data integrity |
| Technical | File format, schema reference, encoding, software version | Supports integration, compatibility, and technical processing |
| Structural | Relationships between data points, part-of hierarchies | Enables linkage across components, systems, and aggregation levels |
| Provenance / source | Source system, contributor identity, data acquisition method | Supports transparency and quality assessment |
| Time-related | Time of validity, time of capture, update frequency | Ensures temporal consistency and use in time-sensitive contexts |
| Rights & access | Access level, usage restrictions, license type | Defines data visibility, rights, and obligations |

## D.2 Minimum data content requirements

Table D.2: Minimum data requirements in a life cycle building information system

| Nr. | Data category | Minimum requirement? | Essential data points |
|---|---|---|---|
| 100 | Master data | (x) | Some but not all master data categories are essential |
| 110 | Identification | x | Identifiers to unambiguously classify building in the context of building portfolios |
| 120 | Building usage | x | Building use type important for overlal context |
| 130 | Actor information | (x) | Ownership information important for legal aspects; other actor information important in real estate management throughout the life cycle |
| 140 | Important dates | (x) | Year of construction and/or year of last renovation often relevant when no specific information is available on the condition of a building |
| 150 | Location and site data | (x) | Address essential for operation and usage |
| 160 | Planning record | (x) | While not necessarily originating from the planning phase, a rough building description is essential for numerous use cases |
| 200 | Inventory data | (x) | Basic inventory data are required |
| 210 | Building geometry | (x) | At least some information about the building dimensions is essential to satisfy actors' information needs |
| 300 | Economic and legal data | (x) | Some legal data are mandatory |
| 350 | Property rights and legal liabilities | (x) | Necessary for legal reasons |
| 360 | Contracts | (x) | Contracts are often relevant for legal certainty |
| 370 | Building permits, approvals, and compliance documents | x | Documents that are legally required and needed throughout essential management decisions in the life cycle |

# D.3 Quality requirements for specific data points

Table D.3: Indication of factors with a strong or medium influence on quality requirements for selected data points

| | | Sensitive / confidential | Long validitiy period | Legal retention requirement | High structurization |
|---|---|---|---|---|---|
| **100** | **Master data** | | | | |
| 110 | Identification | (x) | x | (x) | x |
| 120 | Building usage | | x | | |
| 130 | Actor information | x | x | | |
| 140 | Important dates | | x | | |
| 150 | Location and site data | | x | | |
| 160 | Planning record | (x) | x | | |
| 170 | Construction record | (x) | x | | |
| 180 | Maintenance and usage log | (x) | (x) | | (x) |
| 190 | Real estate management and transaction log | (x) | (x) | | (x) |
| **200** | **Inventory data** | | | | (x) |
| **300** | **Economic and legal data** | | | | |
| 310 | Life cycle cost | (x) | | | (x) |
| 320 | Revenues | (x) | | | (x) |
| 330 | Property value | (x) | (x) | | (x) |
| 340 | Taxes | (x) | | | (x) |
| 350 | Property rights and legal liabilities | (x) | (x) | x | |
| 360 | Contracts | x | (x) | x | |
| 370 | Building permits, approvals, and compliance documents | x | x | x | |
| **400** | **Performance data** | (x) | | | (x) |

# E Appendix chapter 6

## E.1 Building passport, logbooks, files

### E.1.1 Report of the German Enquete Commission

The following text, directly cited from the report of the German Parliament (1998, pp. 180–181), demonstrates that the foundational ideas behind a BP concept were already closely aligned with discussions that have persisted up to the present day.

*„Gebäudepaß mit Energiekennzahlen*

*Fakten und Daten über die bei der Errichtung von Gebäuden verwendeten Baumaterialien sind i. d. R. in der Baubeschreibung niedergelegt, wobei aber Details über die eingesetzten Bauprodukte inkl. Der Bauchemikalien gänzlich, z. T. auch Angaben zum baulichen Brand-, Schall- oder Wärmeschutz fehlen. Im allgemeinen gehen die Informationen nicht über z. B. „schwimmender Estrich" hinaus. Umbaumaßnahmen werden praktisch gar nicht dokumentiert.*

*Im Sinne einer nachhaltig zukunftsverträglichen Entwicklung bedarf es der Informationen über Wohn- und Geschäftsgebäude, die weit über die bisher verfügbaren Daten hinausgehen. So enthält etwa die Baubeschreibung keinerlei Hinweise auf mögliche Schadstoffquellen im Gebäude; vor allem ist unter dem Gesichtspunkt der Optimierung der Lebenszykluskosten bisher versäumt worden, entsprechende Informationen den Eigentümern, Verfügungsberechtigten und Nutzern kontinuierlich zur Verfügung zu stellen. Änderungen am und im Gebäude können erhebliche Folgen sowohl für die ökologische als auch die ökonomische Dimension der Gebäudenutzung haben - die Dokumentation derartiger Änderungen ist i. d. R. recht unzureichend. Der Gebäudepaß ist ein Instrument zur standardisierten Informationserfassung und Informationsweitergabe. Die Informationen gehen aus von Architekten, Baufirmen, Handwerkern etc. und sind bestimmt für Bauherren, Eigentümer, Mieter, Käufer und Nutzer, zum Ende der Nutzung des Gebäudes auch für Behörden, die die Abbruchgenehmigung erteilen und die Unternehmen, die den Abbruch bzw. Rückbau durchführen. Der Gebäudepaß dient der Qualitätssicherung der Gebäudefunktionen. Gebäudepässe sollen einen erheblichen Beitrag zur Transparenz der Lebenszykluskosten von Gebäuden leisten und dadurch die Gefahr ökonomischer Fehlentscheidungen verringern. Es ist in diesem Zusammenhang zu klären, ob der Gebäudepaß der öffentlichen Hand - Planungsämtern, Ordnungsämtern etc. - zur Verfügung gestellt werden sollte, um den Gemeinden Hilfestellung bei entsprechenden Fragen zu geben, z. B. nach dem Erhaltungszustand eines Gebäudebestandes. Für potentielle Gebäudenutzer kann der Gebäudepaß wesentliche Informationen über eventuelle Schadstoffquellen liefern und dadurch einen Beitrag zum vorbeugenden Gesundheitsschutz leisten. Er könnte darüber hinaus Grundlage für ein Gebäude- und Liegenschaftsmanagement sein.*

*Ein Gebäudepaß sollte nach Ansicht des BMBau insbesondere folgende Informationen enthalten:*

- *Dokumentation des Baus und der wesentlichen Umbauten mit Angabe der verwendeten Materialien,*
- *Standardsicherheit/Tragfähigkeit,*
- *Angaben zum Brandschutz,*
- *Beschreibung der Baustoffe, Bekleidungen, Belä- ge, Anstriche, Kleber, möglicher Schadstoffemissionen, Lüftungs- sowie Reinigungsmöglichkeiten, Angabe von Problemstoffen, auch bei untergeordneter Anwendung,*
- *Schallschutz, Belichtung, Dichtheit, Lüftungsmöglichkeiten,*
- *ggf. Messung organischer und anorganischer Schadstoffe sowie Bewertung von Innenraumluftbelastungen,*
- *Altlasten im Grundstücksbereich und ggf. Bodenuntersuchungen,*
- *Angaben zu Wärmeschutz und Energiebedarf (u. a. Wärmedämmung, Heizung, Fenster),*
- *Aufwand zur Bewirtschaftung,*
- *Empfehlungen für die Nutzung,*
- *Beschreibung der Außenanlagen.*

*Die Erstellung des Gebäudepasses könnte bei Neubauten durch die beteiligten Bauingenieure und Architekten erfolgen; für Altbauten müßte ein Modus gefunden werden (z. B. vereidigte Gutachter). Der jeweilige Eigentümer müßte den Gebäudepaß gegenzeichnen. Bei Eigentumsübertragung wäre auch der Gebäudepaß zu übergeben. Der Gebäudepaß sollte für Mieter und Nutzer einsehbar sein. Impulse für einen Gebäudepaß kommen insbesondere aus der Innenraumluft- und Altlastenproblematik sowie dem Gebäuderückbau, der mehr und mehr den schlichten Abbruch ersetzt. In allen diesen Fällen ist es notwendig, entweder das Problemstoffinventar des Gebäudes selbst oder die im Boden verborgenen Schadstoffe genauer zu kennen. Die Einführung des Gebäudepasses könnte zahlreiche Vorteile aus ökologischer und gesundheitspolitischer Sicht mit sich bringen, da bereits die Dokumentation des Einbaus von Materialien dazu anregen wird, über die jeweilige Eignung der Bauprodukte und Bauchemikalien nachzudenken. Weiterhin dürfte eine klare Analyse des gebauten Inventars viele Bauherren dazu veranlassen, sich über Baumaterialien wesentlich mehr Gedanken zu machen als bisher.*

*In ökonomischer Hinsicht soll der Gebäudepaß die Bewertung von bestehenden Gebäuden erleichtern und damit den Erwerb von Gebäuden vereinfachen. Am Gebäudepaß könnte die Beantwortung haftungsrechtlicher Fragen ansetzen. So könnte z. B. die Anwendung dazu helfen, die Beseitigung von Schäden dem eigentlichen Verursacher zuzuordnen. Hier böte sich u. U. ein Feld für die Versicherungswirtschaft. Sozial negative wie positive Folgen werden derzeit nicht erwartet.“ (German Parliament, 1998, pp. 180–181)*

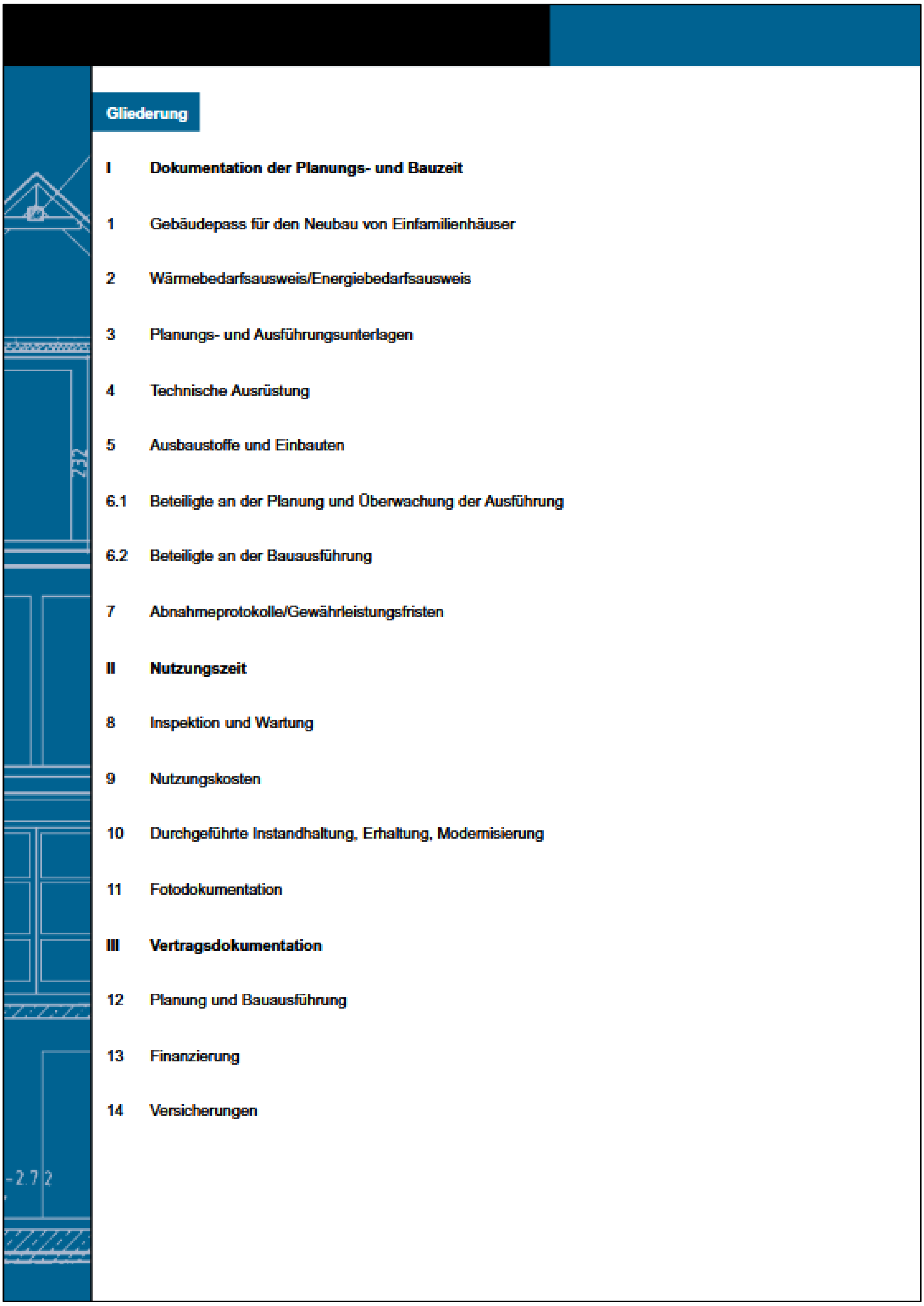
## E.1.2 Official German building passport proposal 2001

The following table shows the content that was proposed by the German Ministry of Transport, Building and Housing (2001) for building passports. In addition to the information that was to be filled in in the form, the explicit extension with appendices, for example in the form of design documents, was intended.

Table E.1: Content of building passports in 2001 based on Ministry of Transport, Building and Housing (2001)

| Nr. | Category | Content |
|---|---|---|
| 0 | General information | Data on location, main actors, important dates, and context of BP creation |
| 1 | Planning laws and building regulations | Land register, building permit and statuary protection information |
| 2 | Landholding | Legal data about the property, access to utilities |
| 3 | Outdoor facilities | Indication and descriptions of outdoor facilities |
| 4 | Buildings | |
| 4.1 | General description | Area data, building usage information |
| 4.2 | Building construction description | Descriptions on main building components |
| 4.3 | Stability / load-bearing capacity | Data points on allowable service loads |
| 4.4 | Fire protection | Indication of special safety requirements |
| 4.5 | Use of daylight / artificial lighting | Data points on illumination |
| 4.6 | Heat protection /energy requirement | Calculated energy demand and information on summertime heat insulation |
| 4.7 | Sound protection | Information on required and measured values of sound insulation |
| 4.8 | Ventilation | Type of ventilation and open air rates |
| 4.9 | Water consumption | Projected / measured values |
| 4.10 | Waste treatment | Basic information on waste disposal facility |
| 4.11 | Equipment and furnishings | Descriptions |
| 4.12 | Building services | Descriptions |
| 5 | Inspection / servicing / maintenance | Documentation of planned and conducted maintenance works for different building elements |
| 6 | Management costs | Documentation of operational costs throughout the first years of usage |

### E.1.3 Official German housing file proposal 2004



**Gliederung**

**I Dokumentation der Planungs- und Bauzeit**

1 Gebäudepass für den Neubau von Einfamilienhäuser

2 Wärmebedarfsausweis/Energiebedarfsausweis

3 Planungs- und Ausführungsunterlagen

4 Technische Ausrüstung

5 Ausbaustoffe und Einbauten

6.1 Beteiligte an der Planung und Überwachung der Ausführung

6.2 Beteiligte an der Bauausführung

7 Abnahmeprotokolle/Gewährleistungsfristen

**II Nutzungszeit**

8 Inspektion und Wartung

9 Nutzungskosten

10 Durchgeführte Instandhaltung, Erhaltung, Modernisierung

11 Fotodokumentation

**III Vertragsdokumentation**

12 Planung und Bauausführung

13 Finanzierung

14 Versicherungen

Figure E.1: Content of the German housing file proposal (BMVBW, 2004)

## E.1.4 Material data sheet proposal for building passports

**Gebäudepass Vollausbau Variante A = Hausakte**

**Gebäudepass Basisvariante = Gebäudematerialdatenblatt**
- Hauptmaterialien und deren Massen

**Allgemeine Gebäudebeschreibung**
- Kurzbeschreibung von Baukonstruktion und technischen Anlagen

**Wartungsbuch/Bauwerksbuch**
- Prüf-, Wartungs- und Instandhaltungsplan mit Prüfanweisungen
- Dokumentation der durchgeführten Prüfungen, Wartungen und Modernisierungen

**Materialbuch**
- Detailbeschreibung der verbauten Bauteile und Materialien mit Informationen zu Trennbarkeit und Rückbau
- Ausbaustoffe (z.B. Fußbodenbeläge, Farben)
- Einbauten (z.B. Sanitärobjekte, Armaturen)

**Energieausweis**

**Dokumentenablage**
- Planungs- und Ausführungsunterlagen
- Technische Ausrüstung
- Beteiligte an Planung und Ausführung
- Abnahmeprotokolle/Gewährleistungen
- Nutzungskosten
- Fotodokumentation
- Verträge

Figure E.2: Material data sheets as an integral part of building passports (Reisinger et al., 2014, p. 88)

### E.1.5 Early European building logbook research initiatives

Table E.2: Overview on early European research initiatives dealing with digital building passports and logbooks

| Project name | Original goal and focus | Reference to DBLs and BPs | Source |
|---|---|---|---|
| ALDREN | Building renovation passports for non-residential buildings | DBLs as a foundation to store relevant data for renovations | (Sesana et al., 2021) |
| BIM4EEB | BIM-based solutions for renovations in residential buildings | DBLs as a foundation to store relevant data for renovations | (Signorini et al., 2021) |
| iBRoad | Individual building renovation roadmaps, renovations plans and extended EPCs for renovations of single-family houses | DBLs as a foundation to store relevant data for renovations | (Libórîo et al., 2018; Sousa Monteiro et al., 2018) |
| X-tendo | Further development of EPCs using innovative technologies and tools | Building logbooks as a data repository for further tools and tasks | (Toth et al., 2021) |

### E.1.6 Policy initiatives on building passports and logbooks

Table E.3 provides an overview of public sector initiatives aimed at developing DBLs/DBPs. While these initiatives often focus on creating structured, centralized repositories of building-related information, the distinction between logbooks and more task-specific tools, such as building registers, is not always clear-cut. In practice, boundaries between these systems tend to be fluid, with overlaps in both function and data structure depending on national priorities, policy frameworks, and implementation contexts.

Table E.3: Overview on policy initiatives on building passports and logbooks based on country, maturity level, degree of liability, and main drivers

| Initiative | Country | Maturity level | Degree of liability | Main driver | Source |
|---|---|---|---|---|---|
| Electronic Building Passport (EBP) | Australia | Tested | Voluntary | Improve data availability for the national building stock | (Miller & Lützkendorf, 2016; Miller et al., 2020) |
| Post Interventi e Dossier | Belgium | Operational | Mandatory | Healthy and safety of building users | (Vlaanderen, 2023) |

| | | | | | |
|---|---|---|---|---|---|
| E-construction platform | Estonia | Tested | Voluntary | Improve public real estate services and information management including 3D view | (e-ehitus, 2025) |
| Woningpas | Belgium | Operational | Voluntary | Improve energy efficiency of the building stock through better data availability | (EC, 2019; Hypotheek.winkel, 2023; Liferay DXP, 2023) |
| Bedrebolig | Denmark | Operational | Voluntary | Support building owners in planning energy renovations | (Energistyrelsen, 2014) |
| Le carnet numérique du logement | France | Operational | Partly mandatory | Support building owners in their information management | (Carnet-numerique.co, 2023) |
| Electronic Building ID | Greece | Operational | Mandatory | Improve transparency in transactions and the knowledge on the national building stock | (Ministry of the Environment and Energy, 2021) |
| Property Register | Iceland | Operational | Mandatory | Keep enriched cadastral data for land management and monitoring of the building stock | (HMS, 2023) |
| Federal Register of Buildings and Dwellings | Switzerland | Operational | Mandatory | Improve monitoring of the national building stock | (BFS, 2022; Federal Statistical Office, 2023) |
| Platform CB'23 | The Netherlands | Under development | Voluntary | Promoting circular economy by systemizing building-related information | (Platform CB'23, 2022) |
| Home Report | United Kingdom (Scotland) | Operational | Mandatory | Improve transparency in transactions | (Scottish government, 2020) |

### E.1.7 Industry initiatives on building passports and logbooks

Table E.4: Overview on industry initiatives on building passports and logbooks based on country and main drivers

| Initiative | Country | Main driver | Source |
|---|---|---|---|
| Ilmastoviisaat Taloyhiöt | Finland | Use of IoT data to find options for low-cost energy efficiency measures | (Ilmastoviisaat taloyhtiöt, 2022) |
| Property Log book | United Kingdom | Providing insight into the record of a building at the time of sale, build or improvement | (Property Log Book, 2023) |
| Homebook | France | Automation and control of building use | (HomeBook System, 2023) |
| Building Renovation Passport | Ireland | Providing logbooks and roadmaps to foster renovations | (Irish Green Building Council [IGBC], 2020) |
| PAS-E | Spain | Passports as a tool to reduce the environmental impact of buildings | (Ciclica & Green Building Council España [GBCe], 2023) |
| BASTA Logbook | Sweden | Logbooks as a project management tool in connection with material databases | (BASTA, 2023) |
| Produktkollen | Sweden | Storing and managing of building-related information as comprehensive documentation and maintenance assistance | (Produktkollen, 2023) |
| Building Passport | United Kingdom | Storing, organizing and sharing of building-related data | (Building Passport, 2023) |
| Digital Building Passport | Poland | Storing and managing of building-related data to support decisions in real estate management, in specific investment decisions | (Digital Building Passport, 2023) |
| CAPSA | Germany | Data platform and application for DBPs including functions to create data and provide assistance in decarbonization decisions, among others | (CAPSA, 2024) |

### E.1.8 Data structure proposal for digital building logbooks

Table E.5: Proposed data structure for a semantic data model of digital building logbooks (Böhms et al., 2023, pp. 31–32)

| Category | Description/Overview |
|---|---|
| Identification | Building identifiers such as Building ID, Building Unit ID, Cadastral Parcel ID, and online link IDs like InspireID. |
| General | Relationships between entities, basic attributes like type/subtype, geo-coordinates, usage function, dates of construction and renovation, and various documents (e.g., BIM models, technical drawings). |
| Legal and Finance | Financial and legal data including property valuation, lifecycle costs, sales data, and related documents like tenancy agreements, insurance policies, and rule violation records. |
| Dimensions | Physical dimensions such as lengths, gross and net areas/volumes, and linked geometric representations (0D, 1D, 2D, 3D). |
| Performance | Building performance indicators like energy labels, utility consumption, emissions data, and indoor health metrics. Includes EPCs |
| Structure & Material | Details of building structure and materials, breakdown of spaces, material properties like U-values, inspection years, and restricted material information (e.g., asbestos). |
| Building Services | Building service systems including energy, ventilation, water, automation parameters, and safety checks. Includes related documents like inspection certificates and maintenance contracts. |

# E.2 Topical passport schemes

## E.2.1 Building resource passport

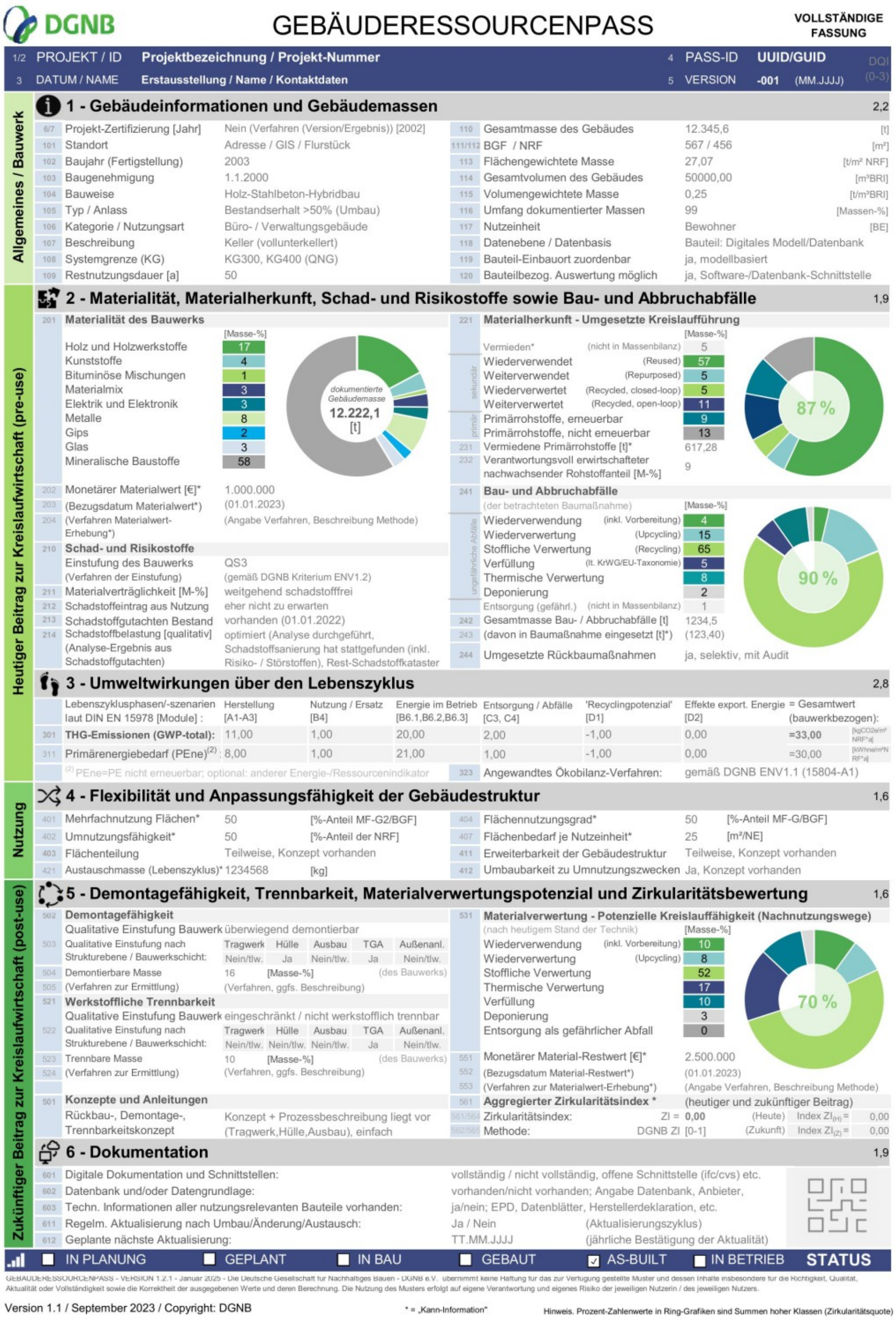


Figure E.3: Example for a building resource passport for existing buildings (DGNB, 2023a)

# E.3 Virtual building models

## E.3.1 Fundamentals of BIM

BIM is frequently interpreted as the solution to digitize the design, construction, and operation of buildings and thus to make all involved production and service processes more efficient and even more effective in terms of achieving targets that are pursued with a building. According to the widespread perception in academia, BIM constitutes a methodology that includes processes of creating, modeling, and visualizing of building-related information with the help of technological and managerial components. However, the concept is sometimes misleadingly regarded as a multi-functional product (Hemmerling & Bähre, 2020, p. 19). For this, BIM needs to be put into the context of specific applications that make use of BIM functions. Sacks et al. (2018, p. 58) distinguish between:

- BIM tools that process BIM-based information for a specific use case (e.g. cost calculation or scheduling tool),
- BIM platforms that enable the creation of a BIM model with functions to maintain the integrity of the model (integrate specific functions like clash detection systems for example),
- BIM servers that store the relevant data,
- BIM environments (CDEs; section 0) that include a set of different BIM applications and act as a multiplatform.

Since the early 2000s, BIM has been an increasingly popular topic in the academic literature. While, in the beginning, the focus lied on the digitization of building design activities through 3D modeling, the possibilities to expand BIM to other occasions and tasks in the building life cycle were explored more and more over time. This led to the enhancement of BIM functionality, the creation and further development of important foundations such as data models, the establishment of new tools for information management based on BIM, and to several research trends. Trends that are noteworthy in the context of building-related information management and LC-BISs will be examined in the following section.

## E.3.2 Current BIM trends

#### N-dimensional BIM and BIM level evolution

One trend has been the enhancement of a 3D BIM model by several additional dimensions and through semantic enrichment. Starting from 2D drawings, the geometry of a building becomes much more tangible through adding a third dimension and visualizing a building as a virtual 3D model. The fourth dimension of BIM addresses the aspect of time enabling a time-based modeling of a construction project. Dimension five refers to economic information in the form of costs. According to Hemmerling and Bähre (2020, p. 60), 6D BIM addresses the extension of BIM to facility management while 7D BIM includes uses cases of sustainability-related aspects. The last two dimensions of BIM are partly swapped in the literature but all in all researchers agree on the idea of seven dimensions. Further extensions are possible.

The consideration of additional BIM dimensions is not the only classification scheme that indicates the potential functions of BIM. The literature defines three (or four depending on the source) maturity levels of BIM (Borrmann, König, et al., 2018b, p. 13; Sacks et al., 2018, pp. 15–16). The highest level implicates a multidisciplinary integrated collaboration on a shared BIM model (Figure E.4).

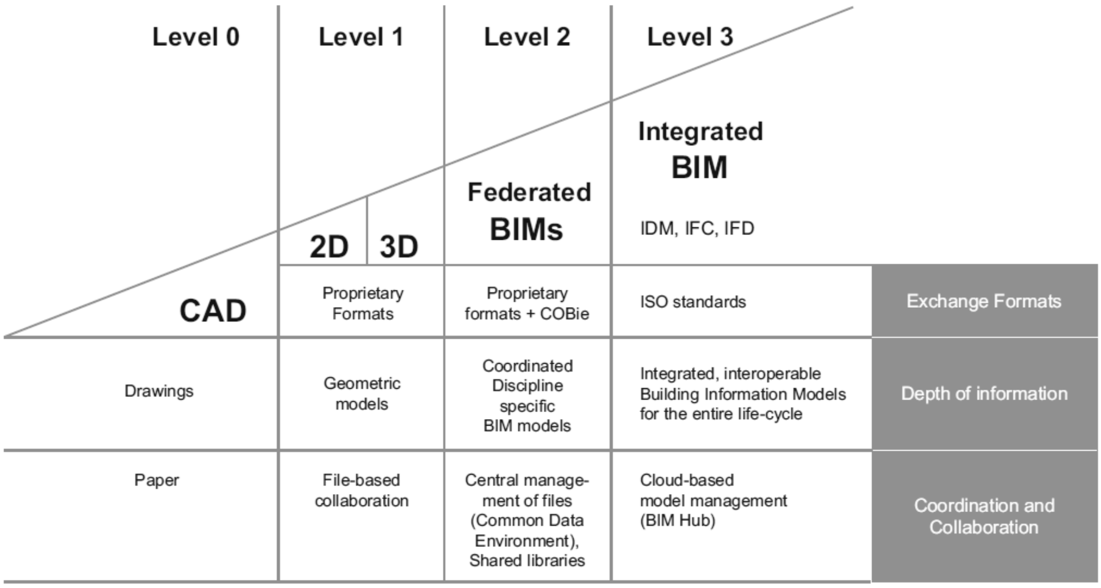



Figure E.4: Maturity levels of BIM (Bew & Richards, 2008 cited by Borrmann, König, et al. (2018b, p. 13))

Objects in BIM models can be classified according to their level of detail (LOD). LOD 600 is perceived as the most detailed level in which objects can be managed dynamically throughout their lifespan and in specific for facility management aspects (Hemmerling & Bähre, 2020, p. 57).

### Building Lifecycle Management

Originally being used as a methodology to digitally design buildings, BIM expanded to the whole life cycle of buildings. Several publications address the idea of life cycle BIM from different stand points including Dalla Valle et al. (2020, p. 50), Jang et al. (2021), Kubler et al. (2016, p. 428), Qing et al. (2014, p. 1), and Xu et al. (2014, p. 8). Sacks et al. (2018, p. 19) describe life cycle BIM as an approach that provides actors with current building-related information while a BIM-based system acts as a single source of information.

A similar concept which incorporates BIM for managing buildings throughout their lifespan, called Building Lifecycle Management (BLM), originates from the idea of Product Lifecycle Management (PLM) (Di Biccari et al., 2018, p. 69; Malagnino et al., 2017, p. 335). Mangialardi et al. (2017, pp. 347–353) compare typical definitions and characteristics for BIM and PLM and derive potential benefits to integrate them under BLM. Both et al. (2013, pp. 20–21) regard BLM as a strategy with technical, organizational, and methodological aspects that works as a framework for a variety of instruments. They define the integration of digital building models and further semantic information as crucial for BLM. Recent studies address the integration of current ICTs for data collection and analysis and of digital twins into BLM (Lennartsson et al., 2020, p. 343; Yitmen et al., 2021). Blampain et al. (2023, pp. 886–887) identify a couple of important requirements for BLM with the help of BIM to unfold its effect. This includes a clear specification of information needs by actors, a translation from conceptual works into technical requirement and interdisciplinary and data-centered thinking.

Another overarching organizational approach for life cycle BIM is pursued by Godager et al. (2021, p. 42265) with their definition of "Enterprise BIM" (EBIM). According to them, EBIM is an extension to BIM with a strong focus on information sharing and collaboration throughout the building life cycle (Godager et al., 2021, p. 42268).

**Collaborative BIM**

Collaborative BIM is a term that stands for the evolution from standalone CAD solutions to fully integrated BIM models in a collaborative environment. This corresponds to the classification into BIM levels while level 3 BIM standing for a collaborative open BIM approach. In this case, building-related data are stored in a centralized repository and ICT capabilities such as cloud solutions are used to enable a digital working environment (Sacks et al., 2018, p. 16). The collaboration in this kind of setting is regarded as crucial for managerial aspects of BIM (He et al., 2017, p. 681). The coordination of different actors can be carried out via a distributed federated BIM data model (Beach et al., 2017, p. 3). For this, specific governance rules are needed to enable a smooth collaboration between the involved actors (Beach et al., 2017, p. 6).

Collaborative BIM simplifies data sharing between actors based on the availability of up-to-date BIM models. Additional exchanges of the same data become redundant. In order to function properly, collaborative BIM relies on structured data formats such as IFC, XML, or COBie (Sacks et al., 2018, pp. 85–86). In the literature, collaborative BIM is primarily perceived as project-oriented and analyzed for actor constellations at the construction stage (Oraee et al., 2017, p. 1298; Pidgeon & Dawood, 2021, p. 793). Pidgeon and Dawood (2021, p. 804) find out that a multicriteria analysis approach can help to keep a high level of collaboration throughout the life cycle of a project. Schapke et al. (2018, p. 259) identify five key areas that must be considered in following a collaborative approach: communication and cooperation, concurrency, roles and rights, versioning, approval, and archiving. Against the advantages of collaborative BIM approaches they also point out barriers such as the challenge of ensuring data quality, computing deficiencies, and availability issues (Schapke et al., 2018, p. 276).

**BIM for facility management and as-built BIM**

Originating from applications in the building design process, the potential use cases for BIM have been extended to several other tasks in the building life cycle. Much attention has been paid in recent years on the use of BIM for facility management and thus on bridging the gap between construction stage and use stage of a building (He et al., 2017, p. 680). Expanding the benefits of BIM to facility management is regarded as a crucial step to enhance the functionality of BIM. BIM data need to be transferred according to the information needs of actors from the construction to the use stage (Borrmann, König, et al., 2018b, p. 10). This includes the conversion of the design model to the as-built model. In case of introducing BIM for an existing building, data need to be collected first before an as-built model can be established.

The literature agrees on a variety of tasks at the use stage connected to facility management that BIM-based tools can support:

- Structural analysis and clash detection
- Maintenance of warranty and service information
- Energy performance and health monitoring
- Space and emergency management
- Refurbishment/maintenance/retrofit planning and execution
- Cost management and quality control (He et al., 2017, p. 681; Pärn et al., 2017, p. 51; Volk et al., 2014, p. 114)

Based on the potential use cases, BIM offers several benefits in facility management on an abstract level such as the improvement of overall building performance and sustainability, the supporting of the life cycle value of a building through constant updating of as-built models and the improvement of cost reliability (Sacks et al., 2018, p. 134). Furthermore, it can augment information exchange processes, improve accuracy of building-related data, and increase the efficiency of identifying task-relevant data (Pärn et al., 2017, p. 47). Further benefits can be found in the literature (Pärn et al., 2017, p. 49). On the other hand, there are challenges for using BIM in facility management that need to be overcome to unlock its full potential. This addresses for example:

- the updating of the design model with as-built information,
- the definition of roles and responsibilities,
- the consideration of BIM data that are relevant for facility management at an early stage in design and construction,
- the insufficient communication between actors,
- additional costs for surveys and data collections,
- cultural barriers, missing knowledge, and collaboration,
- the technical and semantic interoperability between (data from) BIM and CAFM systems,
- missing standards and requirements, and
- the lack of a contractual and legal framework (Kassem et al., 2015, pp. 262–264; Pärn et al., 2017, p. 49; Rogage & Greenwood, 2020, p. 471).

The literature also makes suggestions on possible solutions by especially addressing the technical aspect of data interoperability (Matarneh et al., 2022; Rogage & Greenwood, 2020, p. 472). More recent studies focus on the integration of BIM and ICT such as IoT to leverage the potentials of data collection for facility management and thus enable real-time monitoring (Moretti et al., 2020; Siccardi & Villa, 2023, p. 2).

#### BIM for deconstruction

BIM can cover the whole life cycle of a building including the end-of-life stage. Akinade et al. (2017, p. 267), for example, explore functions of a BIM-based deconstruction tool. They stress the importance of collaboration, visualization, material quantification, planning simulations, and performance analyses. They also refer to the contribution of BIM-based deconstruction tools to BLM (Akinade et al., 2017, pp. 267–269). According to the literature, BIM is applicable to several tasks at the end-of-life stage of a building. This involves the generation of deconstruction plans, the simulation of end-of-life alternatives and deconstruction processes, the possibility to carry out BIM-based LCAs, BIM-aided waste management, and the detection of recycling potentials (Akbarieh et al., 2020; Akinade et al., 2017, p. 268; Volk et al., 2014, p. 114). As a result, benefits such as automated Design for Construction (DfD) possibilities, the shift from a traditional demolition approach to a more frequent deconstructions, the increase in recycling rates, and the reduction of construction wastes are possible.

**Common Data Environments**

The concept of a "common data environment" (CDE) aims to serve as a life cycle-oriented information environment for the BIM-based exchange of building-related data. A CDE is web-based and should support information management and process management (DIN SPEC 91391-1:2019-04, p. 9). It provides the functions and infrastructure in order to supply and verify information in a construction project (DIN SPEC 91391-1:2019-04, p. 14). As a result, a CDE can serve as the technical foundation for collaborative BIM (section 0). According to DIN SPEC 91391-1:2019-04 a CDE fulfills the following functions among others:

- Acting as a Single-Source-of-Information for project-relevant information
- Establishing clear communication pathways between actors of a project
- Ensuring a consistent naming of contents and rules for categorization
- Ensuring data sovereignty for project participants
- Establishing rules for responsibilities and administration
- Keeping data redundant-free, current, and traceable

Similar to the maturity levels of BIM, there are also maturity levels of a CDE. These levels orient on the level of granularity of building information. The more detailed building-related data are stored, the better the information supply. However, the effort for management increases (DIN SPEC 91391-1:2019-04, p. 12).

The data exchange within a CDE is carried out with information containers, i.e. files or directories for example. These information containers can be addressed and categorized with the help of appropriate semantic data. Changes to information containers must be comprehensible. Reference documents can be added in order to link additional information. If involved actors want to share data, they are only visible for the creating party itself first. All access by other project participants must be permitted by the creator or an authorized party. The underlying principle of data exchange is that information that is shared once cannot be altered. This prevents data loss and ensures the permanent availability (DIN SPEC 91391-1:2019-04, pp. 18–26).

Comiskey et al. (2017, p. 247) list some of the main benefits that are associated with CDEs. Based on the shared information environment, a higher level of consistency, efficiency, coordination, and quality can be achieved. In this regard, a CDE can serve as a basis for BIM level 2 and higher.

The concepts of the Project Information Model (PIM) and the Asset Information Model (AIM), as defined in DIN EN ISO 19650-1, further structure information flows along the building life cycle. The PIM aggregates relevant information needed during the planning and construction phase, while the AIM holds structured data necessary for asset management after handover. Both models are managed within the CDE and evolve through defined information delivery cycles (Figure E.5). This standardization can support a consistent and transparent flow of building-related information from design to operation, aligning with the goal of creating a reliable "single source of truth" over the building's life cycle.

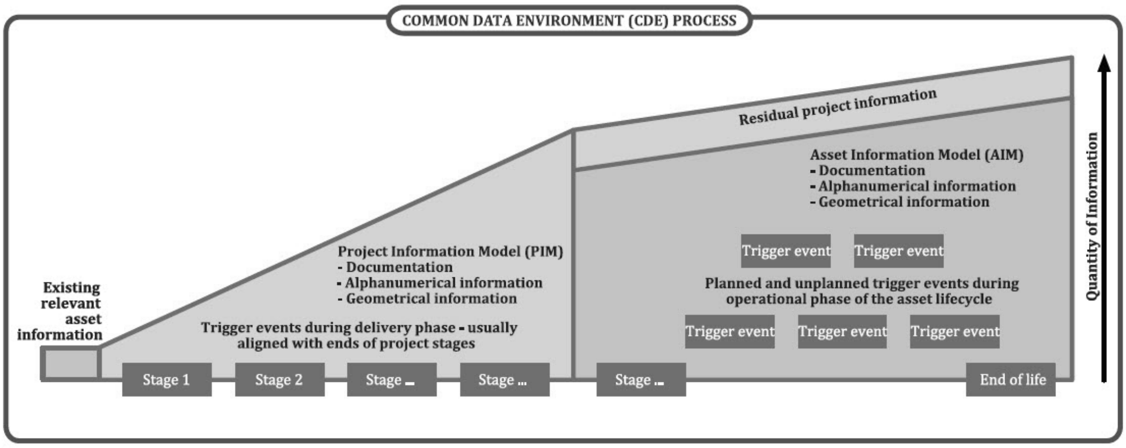



Figure E.5: Information management with the help of Common Data Environments (DIN EN ISO 19650-1, p. 39)

CDEs face notable practical limitations. Multiple non-integrated platforms, reliance on unstructured communication, and manual data handovers undermine data traceability and consistency. High costs, complex workflows, and limited user adoption further restrict their effectiveness across the building life cycle (Jaskula et al., 2022, p. 25).

## E.3.3 Digital twins

**Fundamentals**

Digital twins (abbreviated as "DT" within this section for readability) are often described as digital or virtual representations of a physical object or process. The concept has been implemented successfully in several industries such as the manufacturing, automotive, or chemical industry in order to monitor the condition of a physical object in real time and, above that, gain insights through data analytics on the virtual object (Opoku et al., 2021, p. 10). In recent years, DTs became very popular in the real estate industry which is reflected in the sharp increase of publications (Boje et al., 2020, p. 4; Hosamo et al., 2022, p. 8). A DT can be created throughout the whole life cycle of a building including new and existing buildings (Boje et al., 2020, p. 8). The object of consideration can change to a wider scope from a single building to neighborhoods, building portfolios, cities, and even national building stocks (Boje et al., 2020, p. 3). Similarly, a DT can represent building elements when zooming in (Seaton et al., 2022, p. 11).

A DT works on the basis of a virtual building model, e.g. a BIM model. This model is synchronized on a regular frequency (real time, daily, or other pattern) with data based on the real-world entities and processes. The synchronization is carried out to a certain level of fidelity which can be significant to the use cases of a DT (Seaton et al., 2022, pp. 11–12). For a successful implementation, information management plays a vital role since a large amount of building-related data need to be collected and stored while meeting data quality requirements of the model users. According to Seaton et al. (2022, p. 17) different types of data can be defined with regard to the life cycle stage in which a building currently is. For instance, design and engineering data are collected during early design stages, while as-built data are collected throughout construction and updated in the use stage. A DT is focused on the geometry of a building, but can include economic, legal, consumption, and performance data too (Seaton et al., 2022, p. 32).

### Use cases

There are many potential use cases for DTs throughout the life cycle. Starting in the design phase, a DT can be used to run simulations of the real-world building and thus serve as an experimental environment (Boje et al., 2020, p. 9). In addition, a DT can help to gain insights for an occupant-centric design approach (Hosamo et al., 2022, p. 12). During construction, DTs can support project management tasks by monitoring progress in real time, optimizing construction logistics or detecting safety issues. Furthermore, a DT is assumed to smoothen handover of building-related data to the use stage, when a DT is updated throughout construction (Boje et al., 2020, p. 11). For the use stage, the literature lists benefits for facility management with an emphasize on predictive maintenance based on collected performance data (Hosamo et al., 2022, p. 8; Seaton et al., 2022, p. 9). A multi-functional DT for information management, characterized for example by enabling an interoperable data transfer between BIM, IoT, and facility management tools, is called semantic DT (Hosamo et al., 2022, p. 13). Seaton et al. (2022, p. 9) define five different types of DTs ranging from a descriptive DT to an autonomous and connected DT while the functionality grows with every level. Another term that is used in the literature is "cognitive DT" describing the possibility of DTs to carry out cognition processes such as reasoning, planning, and learning (El Mokhtari et al., 2022; Hosamo et al., 2022, p. 13; Yitmen et al., 2021). Table E.6 lists a selection of the most important functions of DTs.

Table E.6: Use cases of digital twins for buildings

| Functions | Explanation | Evidence |
|---|---|---|
| Prediction | Possibility to predict future states of whole buildings, building components, and building services among others to enable predictive maintenance or optimization measures on building structure or use | (Boje et al., 2020, p. 7; Deng et al., 2021, p. 71; Hosamo et al., 2022, p. 8; Khajavi et al., 2019, p. 147407; Seaton et al., 2022, p. 9) |
| Simulation | Simulating the real building in various stages (design, construction, use) in the virtual environment to draw insights | (Boje et al., 2020, p. 9; Khajavi et al., 2019, p. 147407) |
| Monitoring | Real-time monitoring of the physical building | (Boje et al., 2020, p. 7; Deng et al., 2021, p. 71) |
| Life cycle management | DTs as a basis for managing buildings and the associated processes throughout their life cycle | (Boje et al., 2020, p. 8; Hosamo et al., 2022, p. 7) |
| Sensing | Using sensor technology as a basis for data collection | (Boje et al., 2020, p. 7) |
| Optimization, strategic improvement | Enabling smart resource allocations, cost reductions, and overall better decision-making | (Boje et al., 2020, p. 9; Deng et al., 2021, p. 71) |

### Technologies

DTs are connected to a range of ICTs in order to be effective. First and foremost, the literature names IoT and sensor technology as crucial for enabling real-time monitoring of buildings (Boje et al., 2020, p. 8; Hosamo et al., 2022, p. 3; Khajavi et al., 2019, p. 147407; Seaton et al., 2022, p. 37). Communication between sensor services can be carried out via WSNs (Deng et al., 2021, p. 71). For the sake of data analytics in DTs, the relevance of AI, including ML algorithms, data mining, and big data analytics, is stressed by several papers (Boje et al., 2020, p. 8; Hosamo et al., 2022, p. 2; Lu et al., 2020, p. 392). Other ICTs that are assumed to play a role in DTs are cloud technology (Seaton et al., 2022, p. 13), computer vision (Seaton et al., 2022, p. 36), graph databases (Boje et al., 2020, p. 8), or linked data and semantic web technologies (Boje et al., 2020, p. 3).

### Relation to BIM

There are severe similarities between BIM models and DTs in the built environment, since both concepts represent virtual building models and both can be applied to many tasks in the building life cycle. Studies, such as Deng et al. (2021, p. 61), regard DTs as the highest level form of virtual building models, whereas lower levels are represented by BIM use with gradually less functionality. When it comes to differences, the literature states that BIM is traditionally focused on the design and construction of buildings and compared to DTs not intended to be used with real-time data (Khajavi et al., 2019, p. 147407). While for BIM the primary object of consideration is supposed to be the physical object, DTs stress the relevance of processes and constant changes. Khajavi et al. (2019, p. 147408) distinguish BIM and DTs based on their application focus, the primary users, the supporting technology, available software, primary life cycle stages considered, and the origin of the concept. All in all, BIM is popular within the real estate industry for a longer time and there is slightly more evidence about its functions and characteristics in the literature. However, based on the analysis in this thesis with regard to the requirements of LC-BISs, only very little difference can be identified between the concepts in terms of their role in information management. Thus, an integrated evaluation of their suitability for LC-BISs under the overarching concept of "virtual building models" appears appropriate.

# F Appendix chapter 7

## F.1 Example of a data architecture for digital building logbooks

The data architecture proposed by Böhms et al. (2023, p. 9) is based on the data architecture from the ISO 8000 part 110 standard and was adopted for the needs of DBLs on the EU-level. It consists of the following elements:

- *Data specification*: The data specification is represented by an *ontology* that defines the semantics of data. The ontology indicates how actual content from building-related data should be structured and what possibilities and constraints exist for the content. Thus, the foundation is laid so that data can be correctly interpreted. The ontology relies mainly on two types of abstraction mechanisms, namely a specialization hierarchy, as used for taxonomies, and a decomposition hierarchy, called meronomy.
- *Data dictionary*: A data dictionary is proposed in order to define a standardized terminology for the data ontology. By separating data ontology and data dictionary, the ontology can focus exclusively on the data structure of entities and relationships. The definitions within the data dictionary are based on the INSPIRE terminology (a European Union (EU) initiative aimed at creating a European Spatial Data Infrastructure) where possible.
- *Data specification/dictionary language*: Both, the data ontology and the data dictionary need suitable data modeling languages to enable a standardized modeling view that also sets the basis for their logical and physical modeling/implementation. For the data ontology, a modeling language defines elements, such as 'concept', 'attribute', 'datatype', 'relation', and 'constraint', and for the dictionary 'term' and 'definition'. The DBL semantic data model relies on RDFS for the data ontology and SKOS for the dictionary.
- *Formal syntax*: A formal syntax is needed to transfer the ontology-based data model into a textual and machine-readable format. In the context of linked data and semantic web, one speaks of a '*serialization*' (format). There are different serializations for RDF-based ontologies, such as RDF-XML, Turtle, or JSON-LD. The DBL semantic data model relies on Turtle for its explanations. As part of the syntax, it is also proposed to use SPARQL as a query language and a direct access method.
- *Identification scheme*: In order to unambiguously identify data elements within the data ontology, the dictionary, or actual building-related data content, the use of an identification scheme is proposed. As a starting point, the EC DBL approach should include Universally Unique IDs (UUIDs) and Unique Object Identifiers (UOIs).
- *Metadata*: Metadata are integrated into the data architecture due to their relevance for describing and understanding data sets. Metadata need analog to the actual data content a specification and dictionary. For this, it is proposed within the EC DBL approach to use the W3C Data Catalog Vocabulary (DCAT) which aims to facilitate interoperability between data catalogs on the web (Böhms et al., 2023, p. 10).

The proposed data architecture can be illustrated by outlining the implemented adjustments made to the ISO 8000 part 110 standard.

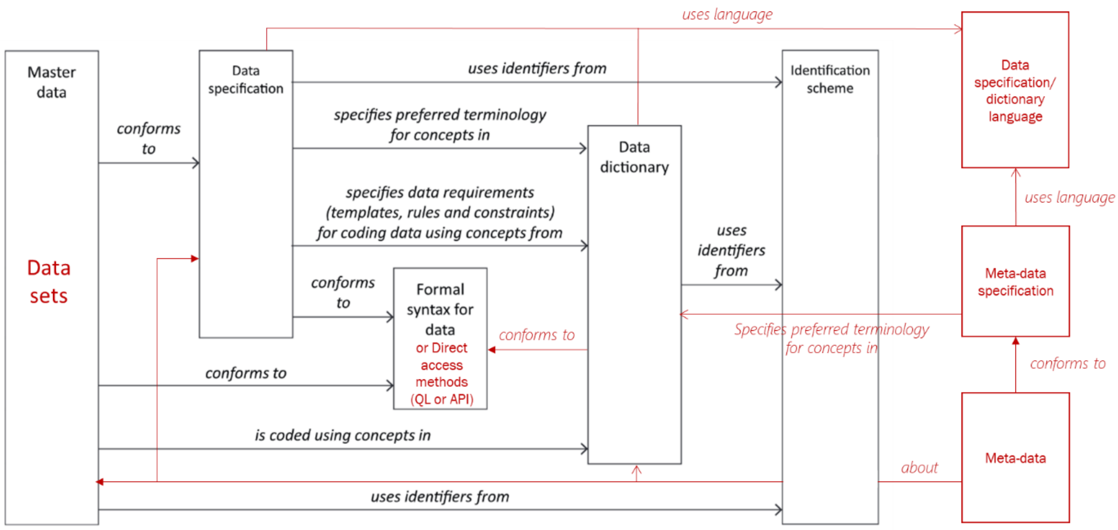



Figure F.1: Data architecture for a semantic data model in digital building passports (Böhms et al., 2023, p. 9)

# F.2 Analysis of data models from the real estate industry

Table F.1: Comparison of existing data models for the real estate industry

| | Strengths | Weaknesses |
|---|---|---|
| IBPDI Common Data model (IBPDI, 2022b) | Covering many important categories of building-related data<br>Detailed concept for definition of entities and relationships | Only incorporates structured data in JSON format<br>Not solely focused on single buildings as object of consideration |
| RICS Data Standard (RICS, 2022b) | Incorporating of relevant use cases, such as due diligence, transactions, formation of DBPs and digital twins<br>Takes into account other construction works than buildings<br>Detailed concept for definition of entities and relationships<br>Covers all types of building-related data | Applicable to structured data in XML or JSON format with few exceptions |

| | | |
|---|---|---|
| OSCRE Industry Data Model (OSCRE International, 2022) | Derivation of entities based on use cases<br>Large library of entities and use cases | Focused more on processes than on building-related data<br>Lack of abstraction mechanisms |
| RESO data dictionary (RESO, 2023) | Attempt for standardization of building-related terms and concepts<br>Large library of entities | Focused more on processes than on building-related data<br>Limited scope according to brokerage needs |
| RealEstateCore (RealEstateCore, 2023) | Ontology-based features, such as knowledge graph presentation and high-level of interoperability | Focus on physical aspects in the ontology |
| Brick (Brick Consortium, 2023) | Ontology-based features, such as knowledge graph presentation and high-level of interoperability | Focus on physical aspects in the ontology |
| W3C Building Topology Ontology (Rasmussen et al., 2021) | Ontology-based features, such as knowledge graph presentation and high-level of interoperability<br>Alignment modules to other ontologies and standards | Limited scope and focus on structural aspects only |
| IFC and buildingSmart Data Dictionary (BSDD) (DIN EN ISO 16739-1:2021-11; Oxlade, 2019) | Detailed building-related data model<br>Availablability in various data formats and schemas creates interoperability | Focus on structural and construction stage aspects<br>Complexity of the schema<br>Lack of flexibility in individual processes<br>Lack of semantic completness |
| EC DBL semantic data model (Böhms et al., 2023) | Orientated on the needs of DBPs/DBLs on EU level<br>Ontology-based features, such as knowledge graph presentation and high-level of interoperability<br>Combination of ontology and dictionary<br>Good basis for further development | Not many details in data representations |
| EU Superhub data structure (Gyuris et al., 2023) | Orientated on the needs of DBPs/DBLs based on research | Strong focus on aggregated data<br>Limited specification of semantics (relationships between entities) |

# F.3 Example for a data model

Within this section, the semantic data model developed by Böhms et al. (2023) to facilitate interoperable DBLs in the EU is explained as an example for an ontology-based modelling approach. It also shows the capabilities of linked data / semantic web implementations based on RDF.

## F.3.1 Data ontology approach for linked data

The data ontology is the core concept of the proposed data architecture in Böhms et al. (2023, p. 10). Ontologies are a powerful concept for semantic data modeling, since they represent the structure and the possibilities for the data content at the same time. Ontology-based approaches have been identified as superior option compared to traditional data exchange standards, if interoperability is the key data quality requirement. Within the ontology proposed by Böhms et al. (2023), the modeling logic is based on RDF. This creates several advantages:

- RDF builds the basis for linked data and semantic web technology, which is slowly but decisively adopted within the real estate domain. Its main benefits lie in the possibility to break up existing information silos, link data across systems and actors, and increase efficiency in data management by avoiding redundancies in data storing.
- RDF enables a high level of semantic and technical data interoperability. It is platform-independent and can link various resources via the internet.
- RDF does not need additional information infrastructure resources, since it can rely on existing internet and web technologies.
- RDF-based ontologies can be illustrated both in graphical form through (knowledge) graphs and in textual forms. For the latter, several serialization formats exist, such as RDF-XML, Turtle, or JSON-LD.
- RDF-based ontologies can be translated to various logical and physical data(base) models. In comparison to ERMs, which are predominantly implemented into relational database models, RDF data can be stored as RDF triple stores, relational data constructs, and in several No-SQL database types.
- RDF-based ontologies offer great flexibility in modeling. Basic constructs are implemented into the W3C RDF language conventions, such as the triple logic and different forms of nodes (Internationalized Resource Identifier [IRIs], literals, blank nodes, quoted triples), while additional constructs, such as classes and properties come along with RDF schema (RDFS) language.

Böhms et al. (2023, p. 16) choose RDFS as the main language construct and propose to extend it with SHACL where needed. SHACL adds closed-world constraints to RDFS meaning that it uses constraints to validate RDF graphs. These constraints, for example, limit the allowed value types, cardinalities, value ranges, string representations, and logical combinations of constraints under certain conditions (Knublauch & Kontokostas, 2018). The combination of different modeling languages in the context of RDF leads to a variety of terms used within the context of the ontology (section F.3.2).

For their semantic data model, Böhms et al. (2023, pp. 17–24) analyzed some of the most important data standards and technologies in order to reach a high level of interoperability between their own approach and these standards while keeping it simple for users. This includes that the approach follows the DIN EN 17632 standard series and specifically DIN EN 17632-1:2023-04 which deals with basics for semantic linking and modeling in the context of BIM. Böhms et al. (2023, p. 26) state regarding the connection with IFC that classes in the DBL ontology can be regarded as subclasses or equivalent classes in IFC. BIM models can be integrated through linkage.

## F.3.2 Foundational concepts of RDF-based data modeling

Table F.2: Terms and concepts applied for RDF-based data modeling based on (Böhms et al., 2023; DIN EN 17632-1:2023-04; Tomaszuk & Haudebourg, 2025)

| Term | Explanation |
|---|---|
| Resource | Anything from the real world can be a resource, such as physical things, documents, abstract concepts, numbers, and strings; similar term for ‘entity’ |
| Class | Group of resources and a resource itself |
| Instance | Members of a class |
| Concept | Another abstract term for ‘class’ to categorize; used in the DBL ontology |
| Aspect | Another informal term for ‘class’ used in the DBL ontology |
| Property | Resource that acts as binary relation between subject resources and object resources |
| Attribute | Another term for property used in the DBL ontology; eventually used differently in native language |
| Relation | Informal term for the connection between resources; used in the DBL ontology |
| Container | Resource that represents collections |
| Collection | List of items |
| Datatype | Defines the range of possible values, such as strings, numbers, and dates |
| Subject | Resource represented by an IRI, blank node, or quoted triple |
| Predicate | Establishes some form of relationship between subject and object; represented by an IRI; denotes a property |
| Object | Resource represented by an IRI, blank node, literal, or quoted triple |
| RDF triple | 3-tuple of subject, predicate, and object |
| RDF statement | Information that can be drawn from a triple |
| Internationalized Resource Identifier [IRIs] | Represents a resource denoted by a string according to a standardized approach; generalization of URIs |
| Literal | Represents a resource used for values such as strings, numbers, and dates |

| | |
|---|---|
| Blank node | Represents a resource for which an IRI or literal is not given |
| Quoted triple | RDF triple that can be used as the subject or object of another triple |
| RDF vocabulary | Collection of IRIs intended for use in RDF graphs |
| Namespace IRI | Common substring for the IRIs in a RDF vocabulary |
| Namespace prefix | Abbreviation for namespace IRIs |

### F.3.3 Critical review

The EC's linked data and semantic web approach for DBLs offers significant potential, particularly in multi-actor environments requiring complex data integration. Grounded in RDF-based data modeling, it aligns well with the needs of governments, public authorities, real estate managers, and other actors operating in data-intensive and interoperable contexts.

Key advantages include its strong focus on interoperability, achieved through RDF and linked data principles, which enable seamless cross-system data sharing and reduce information silos. The use of open standards like RDFS and SKOS ensures scalability and adaptability to evolving industry needs. Additionally, the semantic depth provided by ontologies and data dictionaries enhances clarity and reusability, supporting advanced applications such as policy planning and sectoral reporting.

However, the approach has limitations. Its complexity, particularly in ontology development and infrastructure setup, may deter actors with limited resources, such as small-scale building owners. For single-actor contexts, such as homeowners, the system might be overly sophisticated, as simpler, cost-effective solutions often suffice. Moreover, broad acceptance across diverse jurisdictions and alignment with existing standards remain significant challenges.

In summary, the EC's approach is highly valuable for multi-actor scenarios requiring interoperability and long-term scalability. However, for single-actor use cases or resource-constrained stakeholders, simpler alternatives may be more practical. Balancing these considerations is essential for the widespread adoption of DBPs.

# F.4 Access control strategy

## F.4.1 Factors on attribute-based access control

Table F.3: Factors influencing attribute-based access control in digital building passports

| Subject: user | Object: function | Environment: access conditions |
|---|---|---|
| Personal ID | Complexity (required resources, procedural steps, complexity of actions) | Timing (with reference to building life cycle and specific tasks/processes, time of day) |
| Information on organization (name, size, products, services etc.) | Relevance (value of inputs and outputs) | Location |
| Role/task in the building life cycle (name, service-level agreements) | Resource availability/quality (data, ICT) | |
| Experience level in DBP use (action history) | Output quality (data, requirements for further action) | |

# F.5 Job-sharing between building information systems

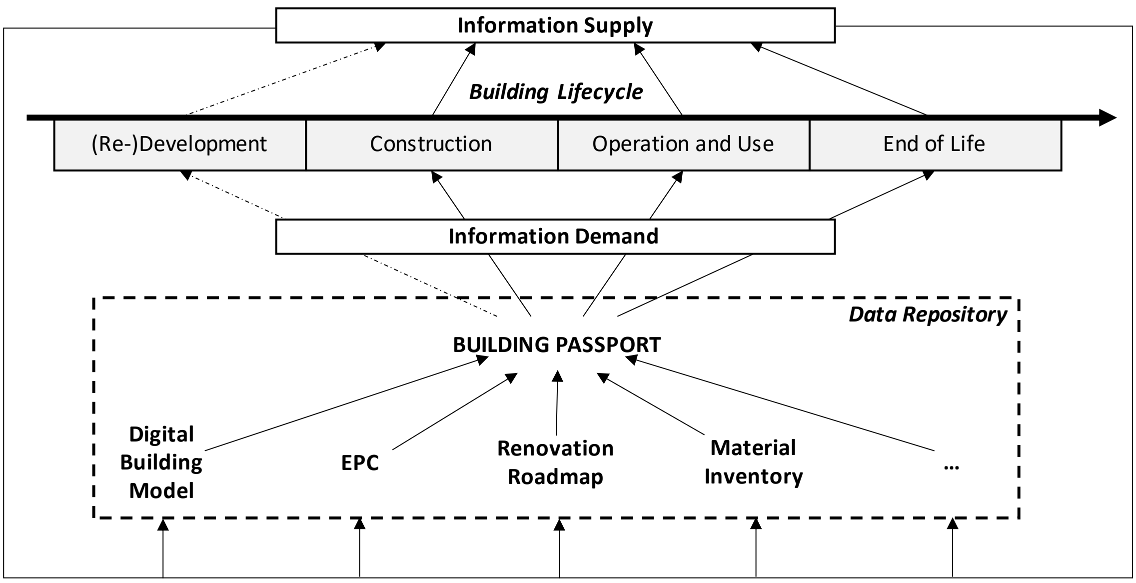



Figure F.1: Conceptual proposal for an integration of selected tools into a digital building passport (Buchholz & Lützkendorf, 2022a, p. 7)

# G Appendix chapter 8

## G.1 Barriers for digital building passports

Table G.1: Barriers for implementing digital building passports in the literature

| Type of barrier | Barrier | Evidence |
|---|---|---|
| Political and legal | Unclear national legislation | Carbonari et al. (2020, p. 16) |
| | Lack of a defined legal framework | Dourlens-Quaranta et al. (2020, p. 9) |
| | EU vs. Member State roles unclear | Dourlens-Quaranta et al. (2020, p. 9) |
| | Redundant public-sector efforts | EC (2023, pp. 27–28) |
| | Insufficient public-sector prioritization | EC (2023, pp. 27–28) |
| | Complexity of implementation projects | EC (2023, pp. 27–28) |
| | Variations in privacy laws | EC (2023, pp. 27–28) |
| | Responsibility for data quality unclear | EC (2023, pp. 27–28) |
| Economic | Benefits not clearly defined | (Carbonari et al., 2020, pp. 13–16; Dourlens-Quaranta et al., 2020, p. 9). |
| | Business model not defined | (Carbonari et al., 2020, p. 16). |
| | Too high costs | (EC, 2023, p. 29). |
| | Lack of sound funding model | (Dourlens-Quaranta et al., 2020, p. 9; EC, 2023, p. 29). |
| | Costs for administration and service provision | (Hartenberger et al., 2021, p. 31). |
| | Different economic interests in the built environment | (EC, 2023, p. 29) |
| Technical | Lack of synergies and consistency with other instruments | (Carbonari et al., 2020, p. 16). |
| | Issues with data accuracy | (Carbonari et al., 2020, p. 16) |
| | Challenges with interoperability | (Dourlens-Quaranta et al., 2020, p. 9) |
| | Data quality issues with existing data sources | (EC, 2023, p. 28) |
| | Unclear data formats, storage locations, and governance | (EC, 2023, p. 28) |

| | | |
|---|---|---|
| Actor-based | Lack of motivation to use and update DBPs | (Carbonari et al., 2020, p. 16; EC, 2023, p. 29; Hartenberger et al., 2021, p. 31) |
| | Limited digital skills and capacities | (Carbonari et al., 2020, p. 16; EC, 2023, p. 28) |
| | Challenges in data management and sharing: | (Dourlens-Quaranta et al., 2020, p. 9; Hartenberger et al., 2021, p. 31) |
| | Data privacy and lack of incentives to share data | (Carbonari et al., 2020, p. 16; EC, 2023, p. 29) |
| | Lack of motivation to use and update DBPs | (Carbonari et al., 2020, p. 16; EC, 2023, p. 29; Hartenberger et al., 2021, p. 31). |
| Tool functionality | Inconsistency around scope and purpose: | (Dourlens-Quaranta et al., 2020, p. 9) |
| | User-friendliness not optimized | (Dourlens-Quaranta et al., 2020, p. 9) |
| | Issues with data governance | (Dourlens-Quaranta et al., 2020, p. 9) |
| | Data quality issues | (Hartenberger et al., 2021, p. 31) |
| | Risks around privacy and data protection | (Hartenberger et al., 2021, p. 31) |

## G.2 Types of business models for digital building passports

Table G.2: Types of business models for digital building passports including their main advantages and disadvantages

| Option | Constellation | Advantages | Disadvantages |
|---|---|---|---|
| B2B or B2C product | A DBP developer sells a DBP product directly to a customer (institutional or private building owner, or relevant stakeholders like property managers). The buyer is primarily responsible for using and managing the DBP. | DBP developers can focus resources on product development; High scalability potential; Customers can customize the DBP product to their needs. | Developers have limited influence on successful product use; Customers receive little support. |

| | | | |
|---|---|---|---|
| B2B or B2C integrated product-service solution | A DBP developer sells a DBP product directly to a customer and provides related services during DBP use. | Comprehensive solution increases trust and support; Clear contact point for customers. | Developer/service provider holds significant power; Potential inefficiencies due to lack of task distribution. |
| B2B or B2C independent product-service solution | A DBP developer sells a DBP product directly to a customer, while independent service providers offer additional services to the building owner. | Specialized service providers enhance efficiency, competition, and innovation. | Requires multiple service agreements. |
| B2B2B or B2B2C contracting solution | A DBP developer sells a DBP product to a customer, who outsources DBP management to a contractor under specific performance agreements. | Contractors incentivized to meet customer requirements; Reduces management burden on DBP owner. | Dependency on contractor skills and qualifications; Reduced control for DBP owner. |
| B2B2B or B2B2C intermediary product-service solution | A DBP developer commissions an agent or distributor to sell DBP products and potentially additional services to customers. | Incentives for agents/distributors promote wider distribution; Synergies with existing business models. | Dependence on intermediary; Potentially higher costs for end-users. |
| Peer-to-peer solutions | Actors in the real estate industry collaboratively develop a DBP solution for their own use. | Immediate alignment with actor needs; Greater harmonization and shared knowledge. | Limited to actors with similar motives and expertise; Lack of specialization in information system development. |