Karlsruher Schriften zur
Bau-, Wohnungs- und Immobilienwirtschaft | Band 12

Matthias Buchholz

Information Management in the Building Life Cycle

The Emerging Role of Digital Building Passports

KIT Scientific Publishing

Matthias Buchholz

Information Management in the Building Life Cycle

The Emerging Role of Digital Building Passports

Karlsruher Schriften zur
Bau-, Wohnungs- und Immobilienwirtschaft
Band 12

Herausgeber
Karlsruher Institut für Technologie (KIT)
Lehrstuhl Ökonomie und Ökologie des Wohnungsbaus
Prof. Dr.-Ing. habil. Thomas Lützkendorf

Eine Übersicht aller bisher in dieser Schriftenreihe erschienenen Bände
finden Sie am Ende des Buches.

Information Management in the Building Life Cycle

The Emerging Role of Digital Building Passports

by
Matthias Buchholz

Scientific
Publishing

Karlsruher Institut für Technologie
Lehrstuhl Ökonomie und Ökologie des Wohnungsbaus

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

Zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften von der KIT-Fakultät für Wirtschaftswissenschaften des Karlsruher Instituts für Technologie (KIT) genehmigte Dissertation

von Matthias Buchholz, M.Sc.

Tag der mündlichen Prüfung: 30. Juli 2025
Erster Gutachter: Prof. Dr.-Ing. habil. Thomas Lützkendorf
Zweiter Gutachter: Prof. Dr. Frank Schultmann

Impressum

KIT Scientific Publishing

Karlsruher Institut für Technologie (KIT)
KIT Scientific Publishing
Straße am Forum 2
D-76131 Karlsruhe

KIT Scientific Publishing is a registered trademark
of Karlsruhe Institute of Technology.
Reprint using the book cover is not allowed.

www.bibliothek.kit.edu/ksp.php | E-Mail: info@ksp.kit.edu | Shop: www.ksp.kit.edu

Print on Demand 2026 – Gedruckt auf FSC-zertifiziertem Papier

ISSN 1863-8694
ISBN 978-3-7315-1478-7
DOI 10.5445/KSP/1000191791

Vorwort des Herausgebers

Die Reihe von Karlsruher Schriften zur Bau-, Wohnungs- und Immobilienwirtschaft wird vom ehemaligen Fachgebiet Immobilienwirtschaft an der wirtschaftswissenschaftlichen Fakultät des Karlsruher Instituts für Technologie (KIT) herausgegeben.

Die Schriftenreihe versteht sich als ein Medium zur Vorstellung von Ergebnissen der wissenschaftlichen Auseinandersetzung u.a. mit Fragen der Planung, Errichtung und Bewirtschaftung von Gebäuden, der Bewertung, Finanzierung und Versicherung von Immobilien, der dynamischen Entwicklung von Gebäudebeständen oder von Trends im Bedürfnisfeld Bauen und Wohnen. Durch die Beiträge soll die Weiterentwicklung von Grundlagen und Ansätzen u.a. der Integralen Planung, der Lebenszyklusanalyse, der Investitions- und Wirtschaftlichkeitsrechnung sowie der Umsetzung von Prinzipien einer nachhaltigen Entwicklung in der Bau- und Immobilienwirtschaft unterstützt und befördert werden.

Mit dem Band 12 wird die am Lehrstuhl Ökonomie und Ökologie des Wohnungsbaus betreute Dissertationsschrift von Herrn Matthias Buchholz zum Thema „Information Management in the Building Life Cycle – The Emerging Role of Digital Building Passports“ vorgestellt.

Die Arbeit verortet sich thematisch im Bereich des gebäudebezogenen Informationsmanagements und gliedert sich damit in das langjährige Forschungsprofil des Lehrstuhls ein. Erstellung, Pflege, Austausch und Interpretation von Gebäudedaten sowohl entlang der Wertschöpfungskette als auch über den Lebenszyklus hinweg sind seit jeher integraler Bestandteil immobilienwirtschaftlicher Aufgaben. Bis heute stellen die damit verbundenen Anforderungen die Akteure des Immobilienwirtschaft weiterhin vor erhebliche Herausforderungen. Ansätze zur Entwicklung und Einführung geeigneter Hilfsmittel und Austauschformate für die Unterstützung des Informationsmanagements bei Immobilien, die nicht nur in Deutschland seit Jahrzehnten diskutiert werden, blieben bisher ohne Wirkung und konnten sich nicht dauerhaft etablieren. Dennoch kann an Vorarbeiten angeknüpft werden, darunter Überlegungen zu Hausakten und Gebäudepässen.

Das Instrument eines Gebäudepasses wurde bereits in seiner ursprünglichen Konzeption als lebenszyklusbegleitende Datensammlung mit der Erwartung verbunden, Vorhalten, Austausch und Aktualisierung gebäudebezogener Informationen sowohl zu ermöglichen als auch zu unterstützen. Getrieben durch die Erfordernisse und Möglichkeiten der Digitalisierung sowie die Anforderungen an ein nachhaltiges Planen, Bauen und Betreiben von Gebäuden steigt aktuell das Interesse an Gebäudepässen und vergleichbaren Instrumenten.

Die hier vorliegende Promotionsschrift von Herrn Buchholz greift die Thematik der Grundlagen für ein Informationsmanagement bei Gebäuden in Kombination mit der Weiterentwicklung des Gebäudepasses auf. Die Arbeit hebt sich in ihrer umfassenden und systematischen Herangehensweise von früheren Veröffentlichungen deutlich ab. Ausgangspunkt ist die Analyse der Informationsbedürfnisse involvierter Akteursgruppen im Immobilienlebenszyklus. Hieraus werden Anforderungen an Instrumente abgeleitet. Vorgestellt wird eine Systematik, mit der Charakter und Ausprägungen entsprechender Ansätze beschrieben werden können. Gleichzeitig werden die gegenwärtigen und zukünftigen Potenziale der Digitalisierung konzeptionell erschlossen, sodass neben einem klar strukturierten Anforderungsprofil ein umfassendes Gesamtkonzept zur Funktionalität digitaler Gebäudepässe entwickelt werden konnte. Hierin ist der wissenschaftliche Wert und Beitrag zur Theorie und Praxis zu sehen. Die Ergebnisse sind in vielfältiger Weise nutzbar und besitzen insbesondere für die aktuell vorangetriebene Standardisierung des Instruments Gebäudepass sowie für dessen Implementierung in der Praxis einen hohen Mehrwert.

Die Arbeit ist in englischer Sprache verfasst und wird unter anderem eine wichtige Grundlage für die im Jahr 2026 auf europäischer Ebene beginnenden Normungsaktivitäten zu digitalen Gebäudepässen (Digital Building Logbooks) liefern. Übrige Leserinnen und Leser wird ein in dieser Form bisher so nicht verfügbarer Einstieg in die Thematik geboten.

Weimar, im März 2026

Prof. Dr.-Ing. habil. Thomas Lützkendorf

Leiter des ehemaligen Lehrstuhls für Ökonomie und Ökologie des Wohnungsbaus

Preface second edition

This publication represents the second edition of my doctoral thesis, written between 2021 and 2025, during which time I served primarily as a research associate at the former Chair of Sustainable Housing and Real Estate at the Karlsruhe Institute of Technology. In terms of content, this edition remains largely identical to the first. With its inclusion in the publication series of the chair, *Karlsruher Schriften zur Bau-, Wohnungs- und Immobilienwirtschaft*, the thesis is now made accessible within a broader academic and professional context.

To enhance precision and comprehensibility, this edition incorporates minor to moderate editorial revisions.

Chapter 2 has been slightly condensed and structurally refined in order to sharpen the focus on the core concepts relevant to the thesis. In particular, introductory sections on real estate management, information management, and information modeling have been streamlined.

In chapter 3, selected subsections were reorganized and condensed to emphasize the essential information management aspects of the analysis without omitting relevant findings.

Chapter 4 was revised selectively to improve readability. The section on data security was condensed to concentrate on the most essential aspects in the context of building information systems.

Chapter 5 remains structurally unchanged. However, individual sections were reformulated to strengthen terminological precision and to sharpen the requirements-oriented perspective.

Chapter 6 remains unaltered.

Chapter 7 was revised in selected passages to clarify and sharpen the presentation of the results and proposed framework, including more explicit formulations of key assumptions and interdependencies within the integrated system architecture.

Chapters 8 and 9 remain unchanged.

The appendix has been shortened, in parts substantially. While the removed sections provided additional background and complementary material, they were not essential for understanding the analytical core of the thesis. These contents remain available in the first edition, and relevant references continue to be included for further study.

The subject of this thesis remains highly relevant to the real estate industry. Recent developments, including initiatives at the European Union level to advance the standardization of digital building logbooks and passports, further underscore the growing importance of structured building-related information management. At the same time, the industry faces increasing pressure to establish future-proof solutions for managing building-related data and information flows, driven by digitization, sustainability requirements, and long-term structural challenges.

This thesis offers an in-depth examination of the fundamental mechanisms underlying building information systems and proposes a structured framework to address them. It is my hope that this contribution supports the ongoing discourse on building-related information management and provides impulses for both academic debate and professional practice.

Karlsruhe, März 2026 *Matthias Buchholz*

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Professor Dr.-Ing. habil. Thomas Lützkendorf. His ability to combine detailed insights with a comprehensive view of the field inspired my early interest in sustainable real estate management. Through his continuous encouragement and constructive criticism, I was able to engage deeply with the subject, sharpen my academic skills, and develop a much clearer perspective on the broader connections within the discipline. I would also like to thank Professor Dr. Frank Schultmann for kindly taking on the role of second examiner and for his valuable time and commitment to this work.

I am also thankful to my former colleagues at the former Chair of Sustainable Housing and Real Estate at Karlsruhe Institute of Technology – Thomas, Daniel, Maria, Kai, and Sonja – who always had an open ear during times of the pandemic and remote work, and who were never too busy for a chat or professional exchange.

My heartfelt thanks also go to my close friends from my student days at Karlsruhe Institute of Technology. Without you, completing my academic education in this way would hardly have been possible, and beyond that, I would have missed out on unforgettable experiences, both then and in the years to come.

I am deeply grateful to my family – my parents and siblings – for their unconditional support and trust in all my endeavors. You have laid the foundation that enables me to pursue both my professional and personal aspirations.

Above all, my deepest gratitude goes to my wife, who had to do without me far too often during the preparation of this thesis, yet remained endlessly understanding and supportive. Her love and care gave me the strength I needed to complete this work.

Karlsruhe, September 2025 *Matthias Buchholz*

Contents

Figures

Tables

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.

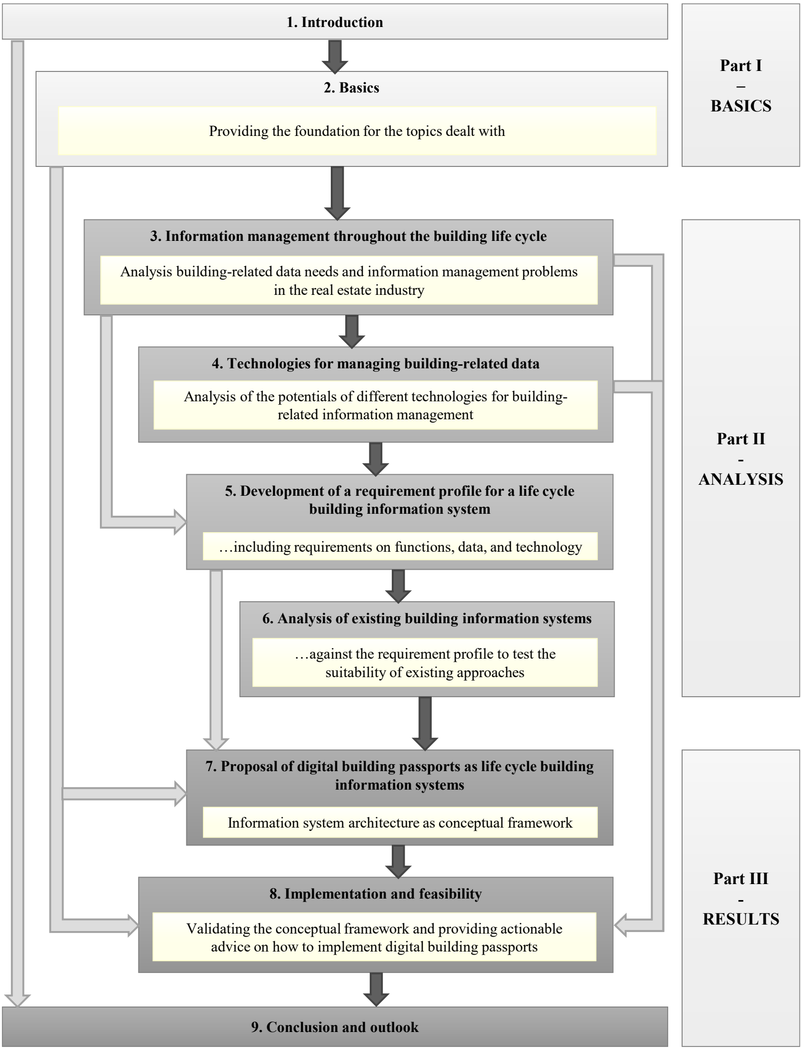


Figure 1.1: Outline of the thesis

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).

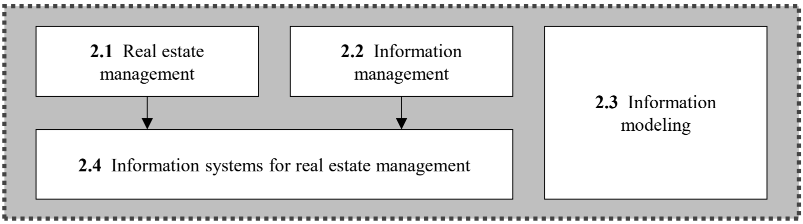


Figure 2.1: Structure of chapter 2

2.1 Real estate management

The fundamentals of real estate management form the background for the examination of more specific issues in this thesis. Thus, main perspectives on real estate are introduced (section 2.1.1). 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 2.1.2. Furthermore, the tasks, which come into play in the various processes of managing buildings throughout their life cycle (section 2.1.3), are of particular importance for the rest of this thesis.

2.1.1 Perspectives on real estate

This thesis builds on the common understanding of real estate as a multidimensional object. Real estate includes not only a physical, 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). 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). 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.

One aspect explored extensively in the literature is the unique characteristics of real estate. In the context of this thesis, attributes such as location dependency, heterogeneity, and high capital intensity implicitly serve as constraints and points of reference. Comprehensive lists and 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).

The real estate industry comprises a variety of actors, each playing a significant role in shaping decision-making processes related to real estate. 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.

A straightforward yet effective method to categorize actors is to use their primary perspective on real estate combined with their main role (Table 2.1).

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.

2.1.2 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). It is divided 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 2.2).

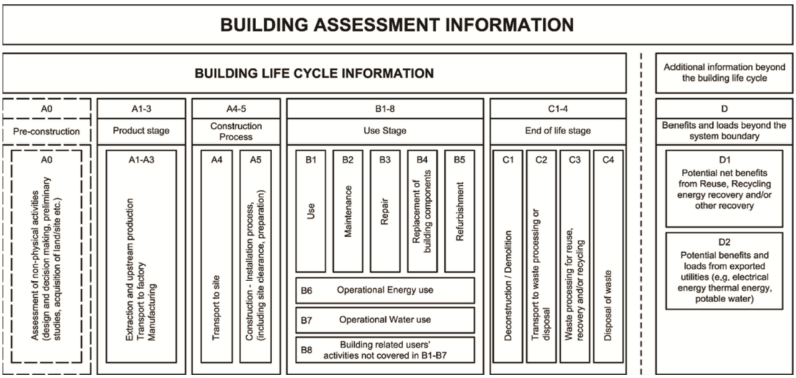


Figure 2.2: Builing life cycle definition in the context of sustainability assessments (DIN EN 15978:2024-05, p. 28)

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.

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.

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 (DIN EN 16310:2013-05, p. 13; Mehlis, 2005, p. 21). The integrated life cycle shown in Figure 2.3 reflects this approach and provides the basis for further life cycle considerations throughout this thesis.

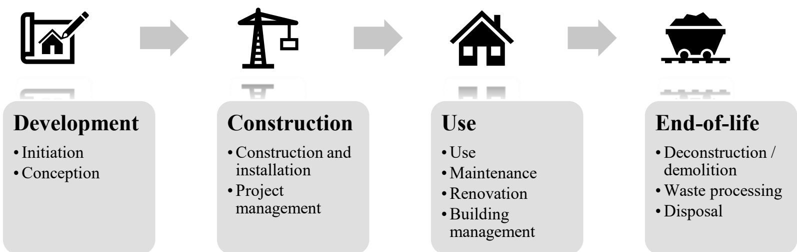


Figure 2.3: Integrated building life cycle

2.1.3 Tasks in the building life cycle

2.1.3.1 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 2.4). 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 2.4 provides a visual representation of the hierarchy and interactions across these levels.

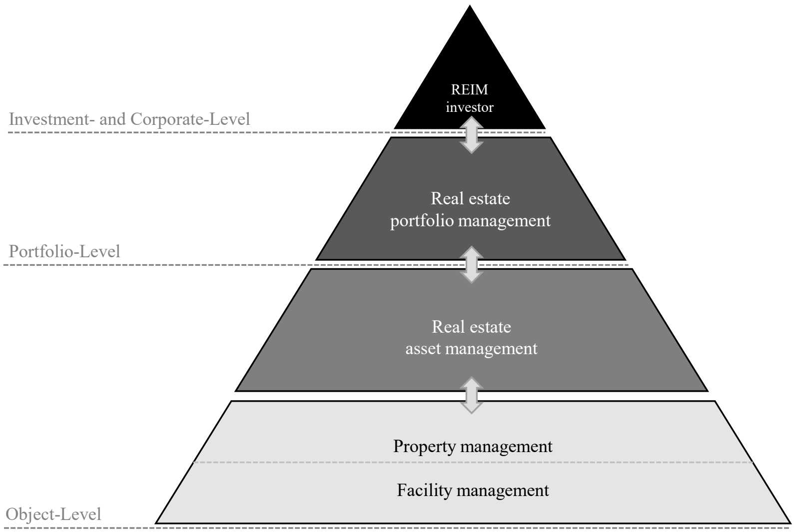


Figure 2.4: Levels of real estate management based on Teichmann (2009, p. 58)

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 2.2).

Table 2.2: Cross-functional tasks in the building life cycle based on (Feldmann et al., 2016; Leopoldsberger et al., 2016; Rock & Hennig, 2016; Rottke, 2017b; Schulte 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.

2.1.3.2 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 (Ausschuss der Verbände und Kammern der Ingenieure und Architekten für die Honorarordnung [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. 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.

2.1.3.3 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 (Figure 2.5).

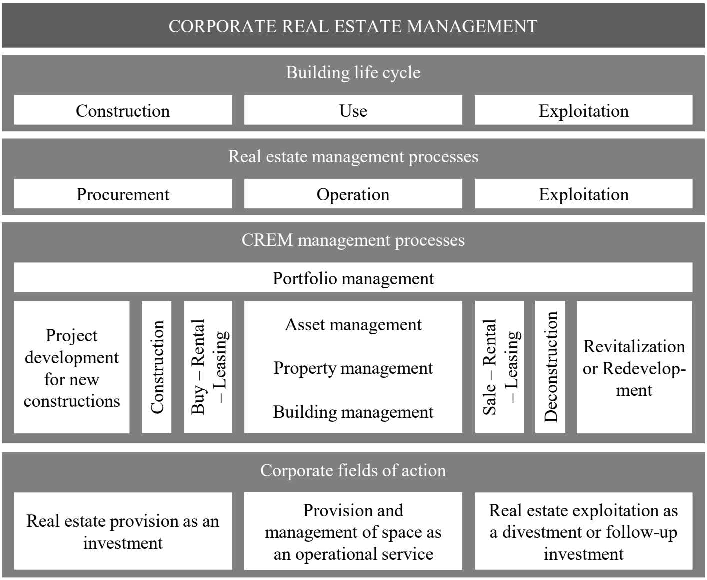


Figure 2.5: Overview on corporate real estate management (Glatte, 2014, p. 27)

For other types of building users, such as non-profit organizations or private individuals, real estate management includes tasks that are specific to their motives and needs.

2.1.3.4 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 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 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 terms and concepts (section 2.2.1), an introduction to information systems (section 2.2.2), and a holistic perspective on the functionality of information management (section 2.2.3).

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 Terms and concepts

2.2.1.1 Data vs information

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. Figure 2.6 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, data are created by applying syntactic rules to symbols. By adding context, data can be transformed into information (Ackoff, 1989, pp. 3–9; Engelmann & Großmann, 2021, pp. 5–6).

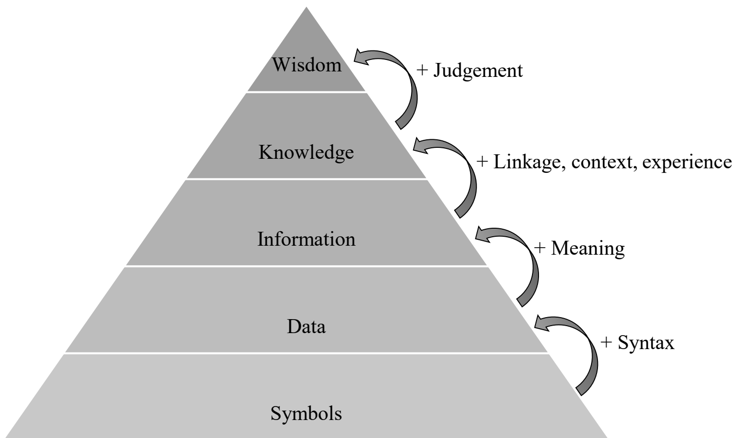


Figure 2.6: Knowledge pyramid based on Ackoff (1989, pp. 3–9) and Engelmann and Großmann (2021, p. 6)

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). 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 The value of 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.

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, such as its intangibility (Krcmar, 2015, p. 16), low reproduction costs (Krcmar, 2015, p. 17), or high transportability (L. J. Heinrich et al., 2011, p. 155).

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. 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 2.7). The intersection of these elements defines the "information stand" of actors, highlighting the alignment, or misalignment, between the information they seek, require, and possess.

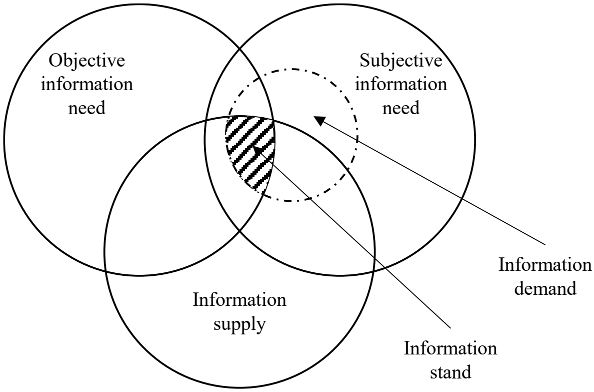


Figure 2.7: Information need and information supply based on Picot and Reichwald (1990, p. 276)

2.2.1.4 Data exchange and sharing

When data are transmitted, they become 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 2.8). Ongoing digitization has increased the possibilities of remote communication.

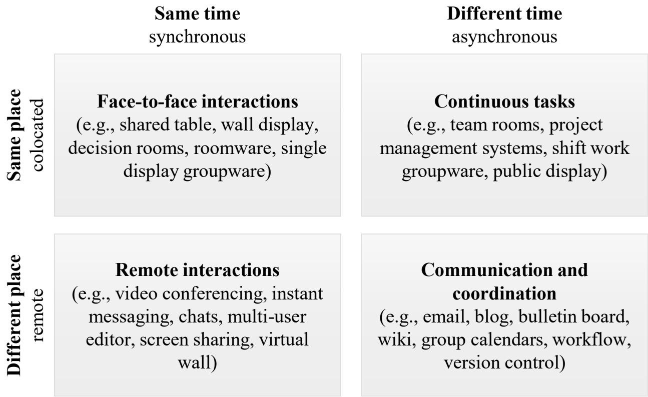


Figure 2.8: Time-space matrix of communication forms (Borrmann, König, et al., 2018a, p. 261)

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 2.9). 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.

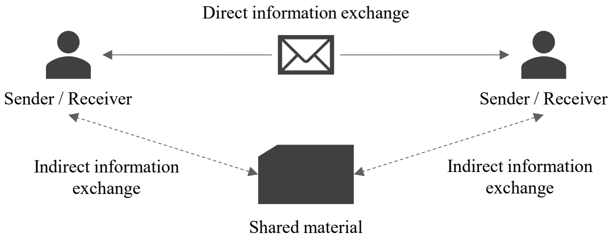


Figure 2.9: Comparison of data exchange and data sharing based on Borrmann, König, et al. (2018a, p. 261)

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).

2.2.2 Information systems

2.2.2.1 Definition

Information systems link data and information and give them a context. The majority of definitions for information systems from the literature overlap in the following characteristics . 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).

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 2.3 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 2.3: 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

2.2.2.2 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. 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).

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 2.10). 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.

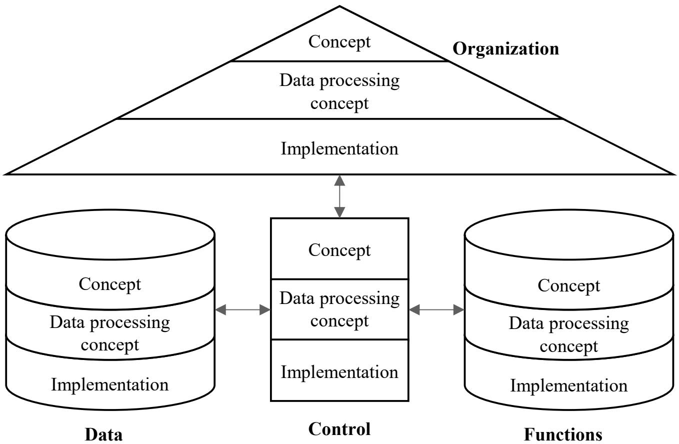


Figure 2.10: Architecture of integrated information systems (ARIS) (Scheer, 1998, p. 18)

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

2.2.2.3 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). Information systems are sometimes also defined as "information and communication systems". 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).

2.2.3 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. Krcmar (2015, p. 107) organizes these tasks in his “life cycle model of 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).

These task areas can be placed in a functional relation (Figure 2.11).

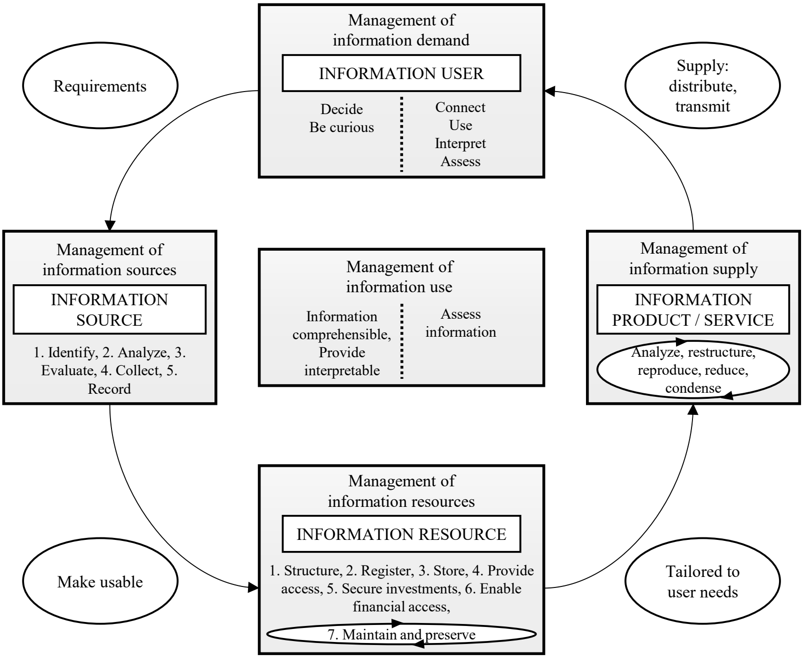


Figure 2.11:Life cycle model of information management based on Krcmar (2015, p. 119)

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 approaches to the modeling of information systems (section 2.3.1), data (section 2.3.2), processes (section 2.3.3), and business implementations (section 2.3.4).

2.3.1 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. They can help in designing, understanding, analyzing, and managing an information system (Krogstie, 2012, pp. 11–12).

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 (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.

2.3.2 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. Typical data modeling languages include the

Entitity-Relationship-Model (ERM), Unified Modeling Language (UML) class diagrams, and the XML schema definition (XSD) language. In the Real estate industry, especially in the AEC (architecture, engineering, construction) domain, the EXPRESS language takes in a prominante role, since it is the original basis for the Industry Foundation Classes (IFC) data schema (Sacks et al., 2018, p. 95).

Besides, Resource Description Framework (RDF) receives increased attention due to its application with linked data and semantic web technology and its potential to enable interoperability between data formats. RDF represents information using a graph-based structure consisting of triples that link a subject to an object through a predicate. This basic structure is illustrated in Figure 2.12

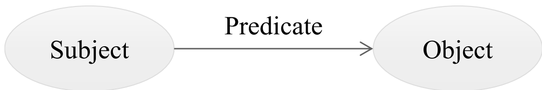


Figure 2.12:Basic RDF triple based on (Cyganiak et al., 2014)

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

2.3.3 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).

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. Several studies 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.

2.3.4 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).

There are structured approaches to business model innovation. 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 2.13). 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).

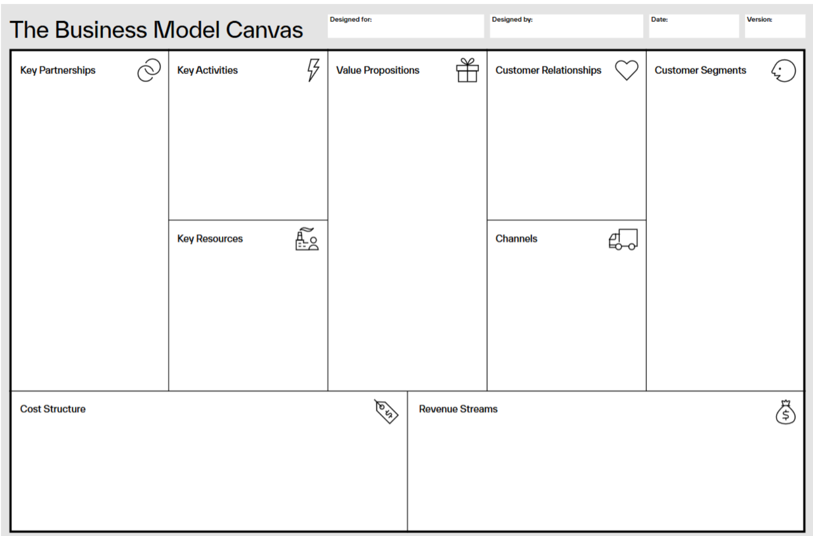


Figure 2.13: Visualization of the business model canvas (Strategyzer, 2025)

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).

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 2.4).

Table 2.4: 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, 2022, 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 19th and 20th century. This development was partly also a result of building regulations and the obligated handover of construction records (Knobloch, 2017). Throughout the 19th and 20th 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 B.6). 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 2.1.3), 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 throughout the building life cycle. Building on the conceptual foundations introduced in chapter 2, this chapter analyzes building-related data, their management processes, and the challenges actors face in using these data effectively across the life cycle.

Section 3.1 defines the scope and categorizes building-related data. Section 3.2 examines data creation and collection processes and their diverse sources. Section 3.3 analyzes data requirements in relation to tasks performed across different life cycle stages, highlighting the complexity of aligning information with task-specific demands. Section 3.4 investigates recurring problems in information management, such as fragmented data, lack of interoperability, and inconsistent data quality.

The results of this analysis provide the basis for deriving the requirement profile for BISs presented in chapter 5.

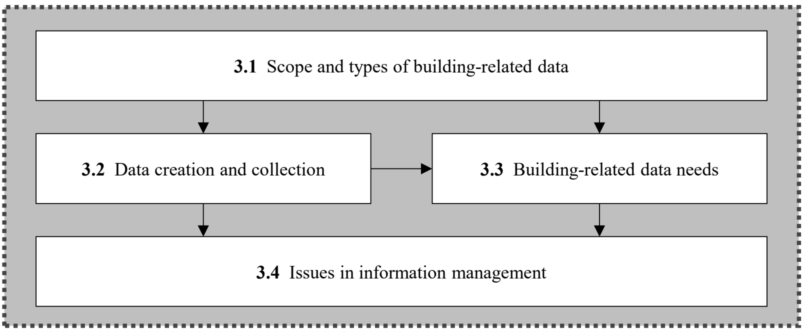


Figure 3.1: Structure of chapter 3

3.1 Scope and types of building-related data

During the life cycle of a building, a large amount of data are generated. This section first develops a definition of “building-related data” (section 3.1.1). Subsequently, approaches for classifying building-related data according to distinguishing criteria are examined (section 3.1.2). This includes systematization approaches from the real estate industry, such as classifications based on building quality characteristics and the determination of building attributes.

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 thesis. Instead, a more precise definition is derived based on the components of the term "building-related data" and is aligned with the definitions of sections 2.1.1 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.

3.1.2 Types of building-related data

The definition of real estate includes the time component as an important dimension (section 2.1.1). 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 size, shape, dimensions and position. They are, for example, planning documents (DIN EN 17412-1:2021-06, p. 7). Several other categories of building-related data can typically be found in theory and practice. Table 3.1 provides an overview on these categories.

Table 3.1: Categories of building-related data based on (Bartels, 2020, p. 39; Turianskyj et al., 2018, p. 233)

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. This includes general market and economic data, broad geographic or climate data are, personal or behavioral data, and regulatory frameworks, unless these data are explicitly connected to a building, its life cycle, or its management.

In theory, building-related data may be classified using a variety of criteria beyond those outlined in Table 3.1. These criteria may include the level of data structuring, the extent of digitization, and whether the data are machine-readable. Their significance varies according to the application context and the specific requirements of the use case.

One of the main situations in which building-related data are required is the description of buildings or their individual elements, for example for documentation or communication purposes. For a structured, data-based representation of a building, building-related properties and attributes play a key role. The terms *property* and *attribute* are well established 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.

Another 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).

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 3.2 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 3.2: 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.

3.2 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 in the building life cycle (section 3.2.1)
- Basics on data collection methods (section 3.2.2)
- An analysis of regulatory systems for data creation and collection (section 3.2.3)

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 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).

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.

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 3.2). By comparison, the intensity of data collection over the life cycle largely depends on the specific data needs and the information demands of the involved actors for different tasks and occasions.

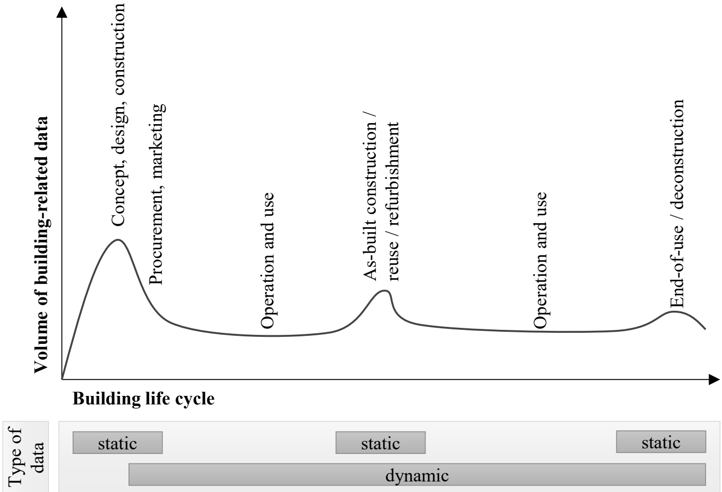


Figure 3.2: Data volume throughout the building life cycle based on Rohde et al. (2011, p. 83)

The actual volume and availability of building-related data 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 information management. These challenges will be discussed further in section 3.4.

3.2.2 Data collection methods

Several methods exist for collecting building-related data. Their development and application are closely linked to data requirements at different stages of the building life cycle. Consequently, the relevance and frequency of use of individual methods vary depending on the specific task or application context. Despite these differences, their common purpose is to enable the systematic collection of building-related data for defined occasions. Figure 3.3 provides an overview of relevant methods and highlights their respective focal points.

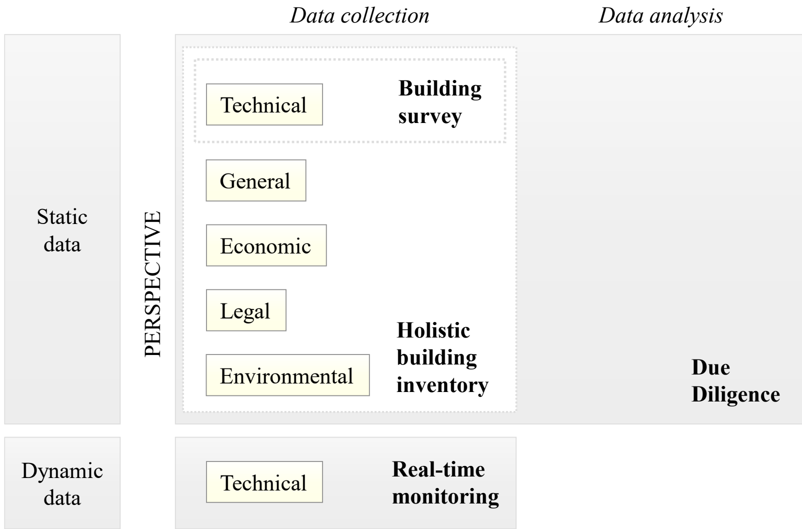


Figure 3.3: Overview on methods for collection of building-related data

A building survey focuses primarily on the systematic acquisition of geometric and technical information describing the spatial structure, dimensions, and physical condition of a building. It is typically applied when existing documentation is missing, incomplete, or outdated, but may also complement available design data with current, as-built information. As such, a building survey provides a detailed technical description of a building at a specific point in time and predominantly captures static data (Donath, 2008, pp. 2–4).

Extending beyond the technical perspective, a holistic building inventory aims at the comprehensive collection of building-related data across multiple domains, including technical, economic, legal, environmental, and organizational aspects. While it may incorporate results from building surveys, its scope is broader and addresses information relevant for management, evaluation, and strategic decision-making. Similar to a building survey, a holistic building inventory represents a snapshot of a building's condition and context and therefore largely consists of static data (Mehlis, 2005, p. 48).

Due diligence builds on these forms of data collection by integrating and evaluating building-related information in order to assess risks and opportunities, particularly in the context of transactions, investments, or major interventions. Rather than constituting a distinct data collection method, due diligence combines and analyzes data obtained through building surveys, inventories, and document reviews from different perspectives, commonly including technical, commercial, legal, and environmental aspects. Its primary function lies in structuring and interpreting existing information to support informed decision-making (Just & Stapenhorst, 2018, pp. 6–7; Royal Institution of Chartered Surveyors [RICS], 2020, p. 4; Tagg, 2018, p. 2).

In contrast to the aforementioned methods, real-time monitoring addresses the continuous collection of dynamic building-related data during the use phase. In this context, real-time monitoring is used as an overarching term, while the literature also refers to technical or in-use monitoring, which focuses on the performance of building systems and technical installations. Based on sensors and metering systems, this approach enables the ongoing observation of parameters such as energy and water consumption, indoor environmental conditions, and system operation. Rather than depicting a static state, technical monitoring supports continuous performance evaluation, operational optimization, and long-term quality assurance during building use (Hajdukiewicz et al., 2015, p. 1; VDI 6041:2017-07, pp. 2–3).

3.2.3 Regulatory systems for data creation and collection

The creation and collection of building-related data are influenced by a range of regulatory systems that define documentation obligations, data scopes, and procedural requirements. The following selection reflects the situation in Germany and focuses on regulatory frameworks that explicitly or implicitly shape building-related data practices. Where appropriate, their contribution to structured information management and BISs is briefly assessed.

3.2.3.1 Regulatory frameworks

Several binding legal frameworks affect the collection of building-related data throughout the building life cycle. The German Honorarium Regulation for Architects and Engineers (HOAI) structures planning and construction services by distinguishing between basic and special services (Table B.2). While documentation activities occur across nearly all project phases, HOAI does not define explicit requirements regarding data quality, data scope, or long-term data usability. As a result, data are often created for phase-specific purposes and remain with individual actors, limiting transferability across life cycle stages. Nevertheless, the systematic structure, legal anchoring, and widespread application of HOAI provide a potential basis for more standardized data creation, particularly in later planning and execution phases.

The German Construction Contract Procedures (VOB), especially Part C, define contractual and technical requirements for construction works, primarily in the context of public projects. Structured around DIN standards (DIN 18299:2023-09, pp. 2–5), VOB C specifies task-related documentation requirements, such as material properties, execution details, and compliance verification. However, these requirements are distributed across numerous individual specifications, resulting in fragmented documentation. This fragmentation hampers the creation of integrated, interoperable datasets and limits the reuse of data beyond their immediate contractual purpose.

More explicitly data-oriented are the “Baufachliche Richtlinien Gebäudebestandsdokumentation” (BFR GBestand), which define standardized documentation requirements for public buildings with the aim of improving real estate management and operational efficiency (Bundesministerium des Innern, für Bau und Heimat [BMI] & Bundesministerium der Verteidigung [BMVg], 2021, p. 1). The guidelines distinguish between alphanumeric and geometric data and define basic and extended documentation scopes (BMI & BMVg, 2021, p. 6). While their application is largely limited to public-sector projects, their structured approach and explicit reference to BIM-based processes illustrate how regulatory frameworks can support systematic data maintenance across life cycle stages. Within the same regulatory context (RBBau), the “Baufachliche Richtlinien Recycling” specify documentation requirements for demolition and material recovery, providing important reference points for data needs at the end-of-life stage (BMI & BMVg, 2018).

Overall, legal requirements in Germany contribute to the creation of substantial amounts of building-related data, but they rarely enforce a coherent, life-cycle-oriented data logic. Data collection is predominantly task- and phase-specific, resulting in limited continuity and interoperability.

3.2.3.2 Standardization frameworks

In addition to legal requirements, numerous standards define conventions for the creation, structuring, and documentation of building-related data. These standards support a shared understanding of terminology, documentation structures, and methodological approaches. Although their application is generally voluntary, their relevance is increased through references in contracts, guidelines, and regulatory frameworks. In Germany, standardization activities are primarily shaped by organizations such as the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), and the German Institute for Standardization (DIN). Table 3.3 provides an overview of selected standards that indicate data and documentation needs across different stages of the building life cycle.

Table 3.3: 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 address a wide range of application contexts, including facility management, building services, property management, commissioning, operation, and demolition. Despite their thematic diversity, they share a common emphasis on structured documentation, classification systems, and data consistency. Several standards distinguish explicitly between construction-phase and use-phase documentation and highlight the importance of transferring and updating data beyond project completion. Others focus on operational processes, maintenance, or end-of-life activities, thereby addressing specific segments of the building life cycle.

At the same time, the standards differ considerably in scope, level of detail, and methodological focus. While some define comprehensive documentation frameworks, others concentrate on specific instruments, such as room books or commissioning records. As a result, their combined application often requires additional coordination and interpretation by project stakeholders.

Taken together, the standards provide a valuable foundation for structured documentation and improved information management. However, their practical impact is limited by fragmentation, overlapping scopes, and the absence of a unifying, life-cycle-spanning data model. These limitations underscore the need for an integrated perspective on building-related data requirements, which is addressed in the following section.

3.3 Building-related data needs

This section analyzes building-related data needs in order to derive requirements for the data content of a BIS. The analysis focuses on identifying which data are created and required for specific tasks and decisions across the building life cycle, and on assessing their relevance in different contexts.

In contrast to earlier studies that primarily examine actors' information demands, such as Starzner et al. (2007) or Rohde et al. (2011), this analysis adopts a task-oriented perspective. It aims to identify objective data needs that arise from decision-making and task execution, independent of individual actors. This approach is particularly relevant in a context where roles and responsibilities in the real estate sector are increasingly dynamic. Compared to earlier task-based approaches as the one from Mehlis (2005), the analysis provides an updated, more systematic and integrated perspective that reflects recent industry developments.

Methodologically, the section combines insights from existing literature with an analysis of typical tasks and decision contexts in the building life cycle. The following subsections first outline the analytical approach (section 3.3.1) and then examine building-related data needs across selected contexts and task areas (sections 3.3.2–3.3.7). The results are synthesized into a hierarchical structure (taxonomy) of building-related data in section 3.3.7.

3.3.1 Analytical approach

The analysis of building-related data needs is based on a task-oriented framework that links data requirements to concrete decision and action contexts in the building life cycle. Rather than focusing on individual actors, tasks are used as the primary unit of analysis, allowing data needs to be derived independently of specific organizational roles.

To structure the analysis, typical contexts in which building-related data are required are identified. These contexts include situations in which tasks are triggered by specific events in the building life cycle (e.g., new construction, refurbishment, transactions), as well as situations in which data are required due to the interests or strategic objectives of actors (e.g., performance assessment, sustainability evaluation, reporting). The concept of such contexts serves primarily as an analytical aid and is not intended as a strict classification.

Based on this logic, a set of relevant contexts and task areas is selected to ensure broad coverage of building-related data needs while maintaining a manageable scope. These include:

- life cycle–related tasks,
- cross-functional tasks,
- public-sector contexts,
- sustainability assessments, and
- reporting-related requirements.

An overview of typical actors and their involvement in these tasks is provided in Appendix B (Table B.7) to contextualize the analysis, although the derivation of data needs itself remains task-based.

The subsequent analysis examines the data required to perform the identified tasks within these contexts and consolidates the findings into a structured taxonomy of building-related data.

3.3.2 Life cycle-oriented tasks

3.3.2.1 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 are master data, which provide 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.

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.

3.3.2.2 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 (section B.4).

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 3.2.2). Table 3.4 outlines key data categories collected through technical monitoring, including operating parameters, energy consumption, system states, and environmental conditions.

Table 3.4: 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 (3.3.5) and corporate sustainability reporting (3.3.6).

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. Compared to professional building owners, their data needs are typically less technically detailed, but more heterogeneous and strongly driven by individual preferences and situational decisions.

3.3.2.3 Data needs at the end-of-life stage

The end-of-life stage, as defined in section 2.1.2, 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.

3.3.3 Cross-functional tasks

3.3.3.1 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 3.5 provides an overview of common property valuation methods and their specific building-related data needs.

Table 3.5: 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.

3.3.3.2 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.

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 3.1.2, further reinforcing the link between sustainability and risk assessment in real estate.

3.3.3.3 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).

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.

3.3.4 Public sector tasks

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).

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.

3.3.5 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
- 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.

3.3.6 Corporate sustainability reporting

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. 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.

3.3.7 Synthesis of building-related data needs

3.3.7.1 Key observations from the analysis

The analysis of task-based data needs across life cycle–oriented, cross-functional, public-sector, and sustainability-related contexts reveals several overarching patterns.

First, the dominant characteristic of building-related data needs is reuse across multiple tasks and contexts. Most data points, particularly master data, inventory data, and legal data, are required repeatedly throughout the building life cycle and across different task areas. This highlights that building-related information is rarely task-exclusive, but instead forms a shared basis for diverse decisions and processes.

Second, differences in data relevance between tasks arise less from fundamentally different data categories than from variations in timing, update frequency, aggregation level, and data quality requirements. While the same core data recur across contexts, their role and required precision change depending on the task and decision horizon.

Third, the analysis shows that data stability is a key distinguishing factor. Some data remain largely static over long periods, either due to physical characteristics of the building or legal constraints (e.g., location, construction type, permits). Other data are inherently dynamic, such as performance, condition, and economic data, which require continuous updating during the use stage and gain importance in sustainability assessment and reporting contexts.

Fourth, truly task-specific data represent only a small subset of building-related information. Even data that initially appear context-specific, such as detailed maintenance records or assessment indicators, often contribute indirectly to other tasks when aggregated, interpreted, or reused.

Overall, these observations indicate that building-related data needs are characterized by high interdependence and temporal continuity, rather than by isolated, task-bound information requirements. This finding provides the analytical basis for structuring building-related data in a unified and reusable manner, as further developed in the following classification approach.

3.3.7.2 Derivation of the classification approach

To systematically condense and structure the building-related data needs identified in the preceding analysis, a hierarchical classification in the form of a taxonomy is derived. This taxonomy represents a bottom-up synthesis of task-based data requirements rather than a predefined data model or an a priori classification scheme.

The choice of a hierarchical structure reflects the empirical findings of the analysis. The recurring reuse of building-related data across multiple tasks and contexts, together with differences in data stability and update dynamics, necessitates a classification that allows both aggregation and differentiation. At the same time, the taxonomy accommodates varying levels of abstraction without requiring exhaustive specification of all individual data points.

At the highest level, the taxonomy distinguishes data domains that group building-related information according to their functional role and temporal characteristics. These domains are directly derived from the analysis of task-specific data needs and include master data, inventory data, economic and legal data, and performance data. Each domain is further subdivided into data categories and, where necessary, into more granular data points (Figure 3.4).

To support clarity, traceability, and extensibility, each element of the taxonomy is assigned an unambiguous identifier using a structured numbering system. This approach follows established conventions in the real estate and construction sector, such as those applied in DIN 276:2018-12 and DIN 277:2021-08, and allows for future expansion of the taxonomy as new data requirements emerge.

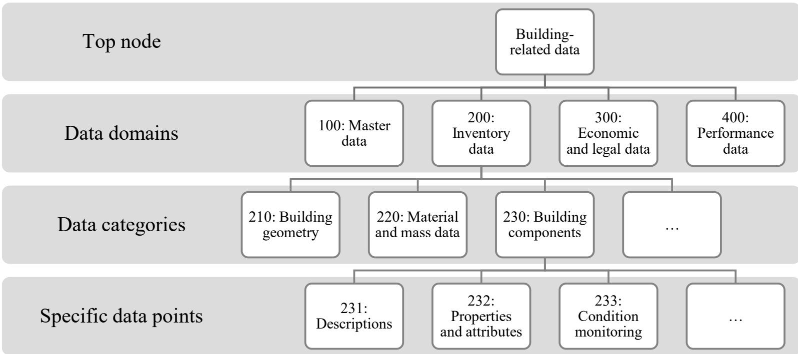


Figure 3.4: Extract from the taxonomy of building-related data

While the taxonomy provides a structured representation of building-related data needs, it does not define data semantics, relationships, or quality requirements. Its purpose is to classify and organize information requirements, thereby providing a foundation for subsequent specification of data models and information systems. A detailed breakdown of the taxonomy including explanations of all categories can be found in section B.5.

3.3.7.3 Master data

Master data constitute the most stable domain within the taxonomy and provide the structural reference for organizing building-related information across tasks and life cycle stages. Their defining characteristic is not task specificity, but their repeated use as identifiers, classifiers, and contextual anchors in nearly all analyzed contexts.

This domain includes data required for unambiguous identification and classification of buildings, such as usage type, location, involved actors, key dates, and planning and construction records. Due to their limited rate of change, master data establish continuity across life cycle stages and enable the consistent linkage of inventory, economic, legal, and performance data.

By structuring master data as a distinct domain, the taxonomy reflects their foundational role in information management and supports reuse across diverse applications. An overview of master data categories is provided in Table 3.6, while detailed explanations are given in section B.5.1.

Table 3.6: 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

3.3.7.4 Inventory data

Inventory data capture the physical and technical realization of a building and represent the core interface between planning, operation, and end-of-life tasks. This domain aggregates information describing geometry, materials, components, technical systems, and functional properties of the built asset.

Across the analyzed tasks, inventory data are required in varying levels of detail and abstraction, ranging from design documentation and facility management to valuation, sustainability assessment, and deconstruction planning. Their relevance is therefore characterized by broad reuse combined with moderate update frequency, particularly during renovations and refurbishments.

The taxonomy consolidates these data into a coherent inventory domain to ensure traceability of physical building characteristics throughout the life cycle. Table 3.7 summarizes the inventory data categories, with detailed descriptions provided in section B.5.2.

Table 3.7: 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

3.3.7.5 Economic and legal data

Economic and legal data structure the financial, contractual, ownership-related, and regulatory dimensions of buildings. This domain reflects data needs arising primarily from valuation, risk management, transactions, reporting, and public-sector supervision.

Unlike inventory data, economic and legal data are shaped less by physical change and more by market dynamics, contractual arrangements, and regulatory frameworks. Their relevance is therefore closely linked to decision-making contexts that require formalized, verifiable, and often standardized information.

By grouping these data into a distinct domain, the taxonomy accommodates the recurring reuse of financial and legal information across tasks while maintaining clear separation from physical building attributes. Table 3.8 provides an overview of economic and legal data categories. Further details are available in section B.5.3.

Table 3.8: 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

3.3.7.6 Performance data

Performance data represent the most dynamic domain within the taxonomy and encompass information on energy use, emissions, environmental impacts, resource flows, and social and functional aspects of building operation. Their growing relevance reflects the increasing importance of sustainability assessment, operational optimization, risk management, and corporate reporting.

A distinctive characteristic of this domain is that performance data are frequently generated through monitoring, calculation, or assessment processes and require regular updating. As a result, performance data often serve both as inputs for decision-making and as outputs of analytical processes, particularly in sustainability-related contexts.

The taxonomy consolidates performance-related information into a separate domain to account for its temporal dynamics and cross-cutting relevance. Table 3.9 summarizes the performance data categories, while comprehensive explanations are provided in section B.5.4.

Table 3.9: 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

3.4 Issues in information management

As shown in the previous section, building-related data are required throughout the entire building life cycle for a wide range of tasks and decision-making processes. In principle, this creates a strong incentive for actors in the real estate industry to systematically create, maintain, and exchange information. In practice, however, substantial deficiencies in information management persist, leading to data losses, inefficiencies, and information asymmetries.

This section examines recurring issues in building-related information management across the building life cycle. It first identifies critical points at which information losses and transfer problems frequently occur (section 3.4.1) and then analyzes structural causes related to actor behavior, industry-specific conditions, and information asymmetries (section 3.4.2). The analysis further shows how these structural issues manifest in data-related problems (section 3.4.3) and discusses their impacts on actors and decision-making processes (section 3.4.4). The chapter builds on relevant literature and selected insights from expert interviews (section B.1)

3.4.1 Critical points in the building life cycle

Critical challenges in information management frequently arise at transition points between life cycle stages, where responsibilities shift and information must be transferred between changing actor constellations. The literature describes such disruptions as media discontinuities, referring to situations in which information is not consistently transferred across stages (Kurzrock et al., 2019, p. 272). These discontinuities impede continuous data retention throughout the building life cycle and contribute to long-term information losses (Mehlis, 2005, p. 171).

The transition from development to construction represents a first critical point. This transition is often fluid, as no standardized definition clearly distinguishes project development from construction. As project complexity and the number of involved actors increase, managing building-related data becomes more challenging. While communication and coordination are emphasized for cost, time, and quality management, structured data transfer is frequently neglected. Changing responsibilities, limited awareness of the future relevance of development stage data, and insufficient tool support contribute to information losses. As a result, essential information such as user requirements or fundamental design decisions may be unavailable in later stages.

A second major critical point occurs at the transition from construction to use. During construction, extensive data are generated on building design, materials, and technical systems. However, ensuring that this information is transferred to building owners and operators remains problematic. Although regulatory frameworks and standards partly require documentation, enforcement is inconsistent and the scope of handover documentation is often unclear or fragmented (Seaton et al., 2022, p. 29). Builders typically have limited financial incentives to provide comprehensive as-built documentation, while building owners may not actively request available data due to a lack of awareness of its long-term value. The absence of clear criteria defining which data must be transferred further exacerbates these problems (Zhu et al., 2021, p. 162). Insufficient knowledge transfer at this stage has long-term consequences for building operation, maintenance, and future interventions (Whyte et al., 2016, p. 3).

The transition from use to end-of-life constitutes a third critical point. With increasing attention to controlled deconstruction and material recovery, reliable information on a building's composition, modifications, and maintenance history becomes essential. Such information depends not only on complete data transfer from construction to use but also on continuous documentation throughout the use phase. When data have not been systematically maintained or updated, significant additional efforts are required prior to demolition or material reuse.

Beyond life cycle transitions, transactions represent a recurring challenge for information management. Potential buyers require building-related information to assess whether properties meet their requirements, yet current owners may be unable or unwilling to provide sufficient data. While due diligence processes can compensate for missing information in larger transactions, they are costly and reflect underlying information asymmetries. These asymmetries are characteristic of the real estate industry and are closely linked to principal–agent constellations discussed in section 3.4.2.3.

Figure 3.5 contrasts two ideal-typical patterns of information handling across life cycle stages: sporadic, task-driven data collection, which leads to cumulative information losses at stage transitions, and a hypothetical continuous retention of information, which serves as a conceptual reference for illustrating the magnitude of these losses.

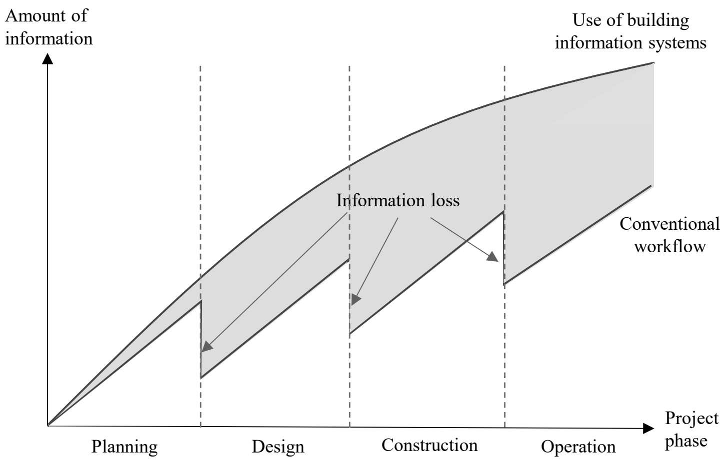


Figure 3.5: Sporadic vs continuous data collection throughout the building life cycle based on Sacks et al. (2018, p. 125)

Overall, the analysis shows that transitions between life cycle stages have a particularly strong impact on the availability and continuity of building-related data.

3.4.2 Strcutural causes of information management problems

3.4.2.1 Actor behaviors and incentives

At the actor level, decisions regarding the creation, maintenance, and exchange of building-related data are strongly influenced by the perceived costs and benefits of information management. A key challenge lies in the long-term character of building-related data: while the effort and costs of data creation typically arise at specific points in time, the benefits often materialize much later, frequently in subsequent life cycle stages and for different actors. Given that building-related data can remain relevant for several decades (Jaskula et al., 2022, p. 6), actors tend to discount future benefits when making short-term decisions.

In addition, actors often struggle to quantify and monetize the benefits of high-quality data, whereas the associated costs, such as time, effort, or investments in tools, are more tangible. This imbalance complicates cost–benefit assessments and reduces the willingness to invest in systematic information management. Uncertainty regarding the future relevance of data and the development of costs and benefits further reinforces this reluctance, particularly as risks and opportunities related to data are rarely integrated into risk management or strategic planning.

Beyond these rational considerations, behavioral and psychological factors also play a role. Data sharing and communication require trust and cooperation between actors, yet the real estate industry is characterized by fragmented responsibilities and limited continuity of collaboration. This can result in conscious or unconscious reluctance to share information, which is often reinforced by mutual blame between actors for perceived failures in planning, construction, or use, a phenomenon described as the vicious cycle of blame (Hartenberger et al., 2008, p. 3).

3.4.2.2 Industry-specific coonditions and market structures

Actor-specific behavior is embedded within broader industry-specific conditions that further constrain effective information management. The real estate industry is characterized by a high degree of fragmentation, both in terms of actor constellations and the instruments used to manage building-related data. Different task areas and life cycle stages rely on overlapping data needs, yet these are addressed through a multitude of isolated standards, tools, and documentation practices. As a result, data are often created repeatedly for specific purposes without being retained or reused across stages.

Another structural barrier is the lack of established business models and market mechanisms that reward investments in information management. Actors who create or maintain building-related data are often not compensated for the long-term value these data generate for others. On the demand side, building owners and other decision-makers frequently do not commission comprehensive data creation because the benefits are uncertain or accrue beyond their immediate scope of action. This weak willingness to pay limits financial incentives for data providers and contributes to the persistence of niche solutions rather than holistic approaches.

Furthermore, the real estate industry is often described as a slow adopter of digital technologies, despite the significant potential of digitization for improving information management (Klinc & Turk, 2019, p. 402). Low levels of digitization and innovation, combined with a lack of widely adopted instruments such as BISs, hinder the systematic integration of data across life cycle stages.

3.4.2.3 Information asymmetries and principal-agent-constellations

Many of the structural challenges described above are reinforced by persistent information asymmetries between actors, which can be explained using principal–agent theory (section B.6). Principal–agent constellations arise when one actor (the agent) holds more or different information about a building than another actor (the principal), for example in relationships between buyers and sellers, landlords and tenants, or clients and service providers (Ceric & Ivic, 2021, p. 2451; Rohde et al., 2011, p. 19).

In the real estate industry, information asymmetries are particularly pronounced due to the heterogeneity, longevity, and limited transparency of buildings. In some cases, both parties lack sufficient information about the building, exposing them to increased risks and uncertainties (Rohde et al., 2011, pp. 19–20). These constellations can result in reduced building or service quality, additional costs, loss of trust, and increased administrative effort (Lützkendorf & Speer, 2005, p. 186).

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).

3.4.3 Data-specific issues

Data constitute a central resource for information management across all life cycle stages of buildings. Throughout their creation, collection, storage, exchange, maintenance, and use, data frequently fail to meet the requirements of actors in the real estate industry. The following data-specific issues are widely discussed in the literature, with the underlying sources approaching information management from different disciplinary and practical contexts, and recur across different life cycle stages and task areas (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).

A first group of issues concerns the availability and accessibility of data. In many cases, required data are missing entirely because they were never created, not systematically collected, or not retained beyond a specific purpose or stage. Even when data exist, actors may be unable to locate or access them due to fragmented storage, unclear responsibilities, or restricted access rights. Such gaps are particularly problematic at stage transitions, where data transfer is required but not sufficiently supported.

A second group relates to data quality and validity. Data may be false, incomplete, inconsistent, or outdated as a result of imprecise data collection, insufficient quality control, or changes to the building that are not properly documented, for example during maintenance or renovation. Over time, originally valid data may lose their relevance if updates are not systematically implemented. These quality issues reduce trust in available data and limit their usability for decision-making.

A third group of issues concerns usability and interoperability. Data may be redundant, irrelevant for specific tasks, or incomprehensible to the receiving actor due to inappropriate formats, excessive volume, or a lack of standardized terminology and data models. Incompatible data structures and systems further hinder the integration and processing of data across tools and organizations, resulting in interoperability problems and inefficient workflows.

Finally, governance-related issues affect the handling of building-related data across the life cycle. Ownership, responsibilities, and operational control over data are often unclear, leading to uncertainties regarding data maintenance, verification, and sharing. These issues are frequently accompanied by a lack of trust between actors and insufficient mechanisms for data quality assurance, which further aggravate existing information asymmetries.

Taken together, these data-specific issues occur across all life cycle stages of buildings and affect a wide range of actors and task areas in the real estate industry. Their persistence and recurrence highlight that deficiencies in data availability, quality, usability, and governance are not isolated phenomena but constitute a systemic challenge for building-related information management.

3.4.4 Impacts of poor information management

The information management problems described in the previous sections lead to a range of negative impacts for actors and decision-making processes in the real estate industry. These impacts, which are discussed in the literature and synthesized here based on existing analyses (Hartenberger et al., 2021, p. 13), often do not occur in isolation but reinforce each other over time and across life cycle stages.

One major impact concerns financial losses and additional costs. Missing, inaccessible, or inconsistent data frequently require regeneration, repeated data collection, or extensive verification efforts. These activities increase transaction costs for building owners, users, and service providers and may lead to inefficient allocation of resources throughout the building life cycle.

Poor information management further results in increased risks and uncertainties. Incomplete or unreliable data impair the assessment of technical, financial, legal, and environmental risks, limiting the ability of actors to make well-informed decisions. This is particularly critical in contexts such as investment decisions, renovation planning, and compliance with regulatory requirements.

Another impact relates to operational inefficiencies and productivity losses. Fragmented or poorly structured data hinder coordination and collaboration between actors, especially in many-to-many communication settings. In building operation and facility management, inadequate data availability can disrupt workflows, delay interventions, and reduce overall process efficiency.

Deficiencies in information management also affect trust and transparency. When data are inconsistent, outdated, or unverifiable, confidence in their reliability decreases, which can undermine cooperation between actors. Unequal access to information further contributes to information asymmetries, distorts negotiations, and may exacerbate existing principal–agent problems.

Finally, poor information management constrains strategic asset and portfolio management. Without a coherent and reliable data foundation, it becomes difficult to assess building performance, identify optimization potentials, or develop long-term strategies. As a result, opportunities for improving operational performance, planning renovations, or enabling future-oriented approaches such as material reuse or adaptive use are frequently missed.

3.4.5 Summary of issues and solution approaches

The analyses in sections 3.4.1 to 3.4.4 have shown that problems in building-related information management in the real estate industry arise from the interaction of multiple, interdependent factors. Information losses occur repeatedly at transitions between life cycle stages, are reinforced by fragmented actor constellations and communication structures, and are further aggravated by persistent data-specific deficiencies. Over time, these problems accumulate and lead to significant negative impacts for actors and decision-making processes.

Figure 3.6 synthesizes the previously discussed actor-related, data-related, and process-related aspects of information management problems by illustrating their interdependencies within typical actor and communication constellations in the real estate industry. Rather than representing a single problem dimension, the figure highlights the structural complexity underlying information management and helps explain why deficiencies persist across life cycle stages despite the availability of data in principle.

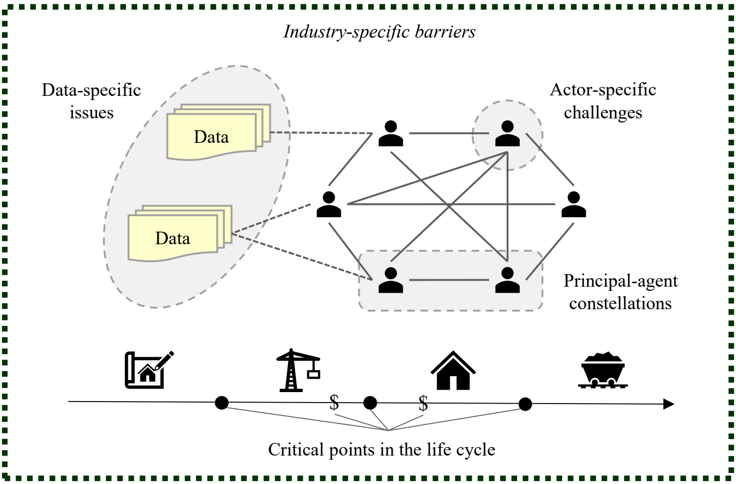


Figure 3.6: Overview on common issues in building-related information management

Given this systemic character, it is unlikely that isolated or purely incremental measures can sufficiently address the identified problems. Effective improvements in information management therefore require a combination of complementary approaches that jointly target organizational processes, data quality, technological support, and the surrounding economic and regulatory framework conditions.

To structure this solution space, Table 3.10 distinguishes several dimensions of information management solutions according to their type, level of application, and degree of regulation. These dimensions include improvements in process quality, enhancements in data quality, the use of information and communication technologies, and the application of assisting instruments and tools. The table does not represent a catalogue of concrete measures but serves as an analytical framework for classifying different approaches and understanding their scope and limitations.

Table 3.10: 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 classification in Table 3.10 illustrates that approaches to improving information management in the real estate industry address different problem dimensions and operate at different levels of application. Process-oriented measures, improvements in data quality, technological support, and the use of assisting instruments and tools are complementary rather than mutually exclusive. As the deficiencies identified in this section are systemic and interdependent, isolated measures targeting only a single dimension are unlikely to be sufficient on their own.

Within this structured solution space, BISs can be understood as one class of assisting instruments that relates to several of the identified dimensions. Their relevance in the context of this thesis lies in their potential to connect organizational, data-related, and technical aspects of information management. At this stage, BISs are therefore positioned neither as a predefined solution nor as a stand-alone measure, but as an object of further analysis within the broader set of possible approaches.

3.5 Summary

Chapter 3 analyzed information management throughout the life cycle of a building as one analytical basis for deriving requirements for a holistic BIS. The chapter focused on building-related data, their creation and use across life cycle stages, and the challenges associated with managing these data in the real estate industry. The following key findings were derived:

- Building-related data constitute the core resource of building-related information management. A clear definition of the term supports navigating the large amount and diversity of data handled by actors in the real estate industry. In this thesis, building-related data are understood as quality characteristics and properties referring to individual buildings, encompassing both static and dynamic data.
- Building-related data are created throughout the entire life cycle of buildings. Multiple opportunities exist to collect these data at the time of their creation. Standards and regulatory frameworks provide specifications regarding which data should be collected, particularly for the transition from the construction stage to the use stage.
- Across all life cycle stages, actors require building-related data to fulfill their tasks. The analysis of task areas and their data needs, as well as similarities and differences between these needs, represents a novel perspective in the research field. The findings indicate a high overall demand for building-related data combined with substantial overlaps between task areas, which informed the development of a taxonomy of core data and documents for real estate management.
- The real estate industry faces significant challenges in information management. Building-related data are often insufficiently available, leading to losses in efficiency and transparency, reduced value creation, and additional costs. These challenges arise from a combination of actor-specific behavior, industry-specific structures, and systemic information management deficiencies. At the same time, different approaches for

improvement exist, including organizational, regulatory, and technological measures.

Overall, the analysis highlights a lack of life cycle-oriented, cross-task, and cross-actor approaches to data storage, maintenance, and use. The findings of this chapter provide an essential foundation for the subsequent derivation of a requirement profile for BISs 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.

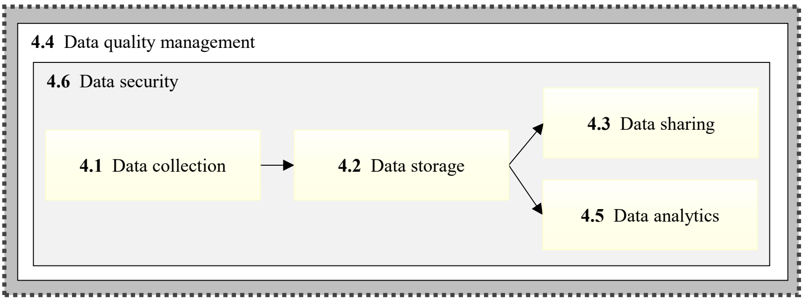


Figure 4.1: Structure of chapter 4

4.1 Data collection

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

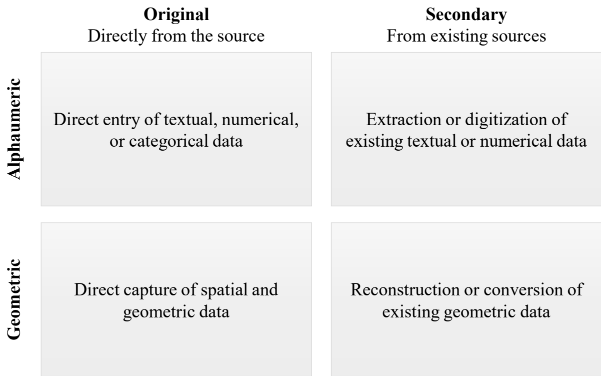


Figure 4.2: Differentiation of different types of data collection

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. From a BIS perspective, this differentiation is essential because it determines which data can be natively integrated, which require transformation, and where information loss or quality degradation is most likely to occur.

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).

Geometric data collection technologies are typically not part of BISs themselves but operate as upstream systems whose outputs strongly shape the usability of building-related data. From a BIS perspective, the critical requirement is therefore not the operation of survey technologies, but the ability to ingest, validate, version, and semantically enrich geometric datasets in standardized and interoperable formats. The effectiveness of geometric data collection for BISs lies in its capacity to provide accurate and structured information that can be seamlessly integrated into digital representations such as BIM models and digital twins. While advances in automation, including scan-to-BIM workflows, data cleansing, and semantic enrichment, have improved integration efficiency, manual intervention remains necessary for complex geometries and heterogeneous existing buildings. Ensuring interoperability between geometric data sources and BISs thus remains a central requirement across building life cycle stages (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. 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). For BISs, these storage-related decisions are not primarily technical choices but long-term design decisions that affect scalability, interoperability, governance, and data quality across the building life cycle.

4.2.1 Architectural patterns and storage paradigms

Different architectural patterns provide alternative ways of organizing data storage and processing in information systems, each involving specific trade-offs regarding scalability, modularity, control, and resilience (Table C.2). In the context of BISs, these patterns are not ends in themselves but design options that influence how building-related data can be managed over long life cycles and across multiple actors.

Traditional client–server architectures enable centralized data storage and controlled access, supporting data consistency and enforceable security policies. However, as the number of users, data sources, and transactions increases, scalability limitations may arise, often requiring additional infrastructure or cloud-based extensions. Tiered architectures address some of these limitations by separating system functions across multiple layers, improving modularity and integration capabilities at the cost of increased system complexity. Peer-to-peer (P2P) architectures, by contrast, support decentralized data exchange without a central authority, enhancing resilience and reducing single points of failure. These advantages come with higher coordination and synchronization requirements and may be constrained by heterogeneous computing power and network quality among peers (Hansen et al., 2019, p. 612; Krcmar, 2015, p. 347; Sunyaev, 2020, pp. 36–44)

For BISs, these architectural patterns are relevant primarily in terms of governance and control. Centralized and tiered approaches can simplify access management and responsibility allocation, while decentralized approaches can support collaborative, multi-actor data environments.

Microservices architecture represents a more recent development that is particularly relevant for BISs with evolving requirements. Originating from service-oriented architecture (SOA), microservices decompose system functionality into fine-grained, independently deployable services that communicate via APIs. APIs enable standardized, automated data exchange between software systems by defining how data and functions can be requested and provided. Compared to monolithic systems, microservice architecture enables selective scaling, incremental updates, and the integration of heterogeneous technologies. These characteristics are especially advantageous for BISs, which must accommodate new data sources and analytical functions over time. At the same time, microservices introduce challenges related to service orchestration, data consistency, and inter-service communication, requiring robust coordination mechanisms (F. Auer et al., 2021; Bushong et al., 2021; Söylemez et al., 2022).

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.

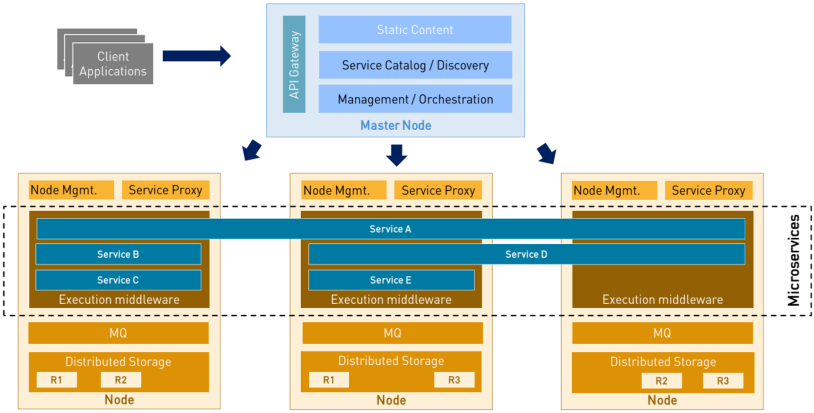


Figure 4.3: Example for a microservice architecture (Kehrli, 2021)

Closely related to architectural patterns are data storage paradigms, which define how data are physically distributed across systems. Centralized storage offers simplicity and direct control but introduces single points of failure. Distributed and parallel systems improve scalability and resilience but rely on reliable network infrastructure and synchronization mechanisms. Federated storage models, which are particularly relevant for BISs, provide unified access to heterogeneous and autonomous data sources while preserving local control. This enables cross-organizational data integration but increases complexity in terms of interoperability, consistency, and governance (Rahm et al., 2015, pp. 43–74).

The choice of architectural pattern and storage paradigm is often constrained by existing technology stacks, organizational structures, and regulatory requirements. Nevertheless, understanding these options provides a conceptual framework for designing BISs that balance scalability, interoperability, and long-term data governance. In multi-actor and life cycle-oriented contexts, decentralized and federated approaches offer particular advantages, while centralized components may remain appropriate where simplicity and control are 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 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.

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.

More recently, distributed hybrid infrastructures have emerged, integrating on-premise systems, private clouds, and public cloud services into a coordinated architecture. Such approaches allow organizations to retain governance over critical data while leveraging cloud-based analytics, collaboration platforms, or AI services (Susnjara & Smalley, 2026). For BISs operating across organizational boundaries and life cycle stages, this architectural flexibility can enhance long-term adaptability.

4.3 Data sharing

Effective data sharing in BISs requires addressing interoperability at multiple, interrelated levels. Building-related data must not only be exchanged in compatible technical formats but also interpreted consistently across systems, organizations, and life cycle stages. This section therefore distinguishes four complementary layers of data sharing. Data formats define the syntactic structure of exchanged information (section 4.3.1). Linked Data and Semantic Web technologies enable machine-readable semantics and the integration of heterogeneous datasets (section 4.3.2). Building-related data standards establish shared conventions and governance frameworks (section 4.3.3). Platforms and data rooms operationalize data exchange within controlled collaborative environments (section 4.3.4). Each of these layers addresses specific interoperability challenges but remains insufficient in isolation. For BISs, effective data sharing emerges from their coordinated use, requiring systems that integrate formats, semantics, standards, and platforms into a coherent information management framework.

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.

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 2.3.2), 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. From a BIS perspective, data formats provide the technical basis for data exchange but do not ensure consistent interpretation or semantic interoperability on their own. Their effectiveness therefore depends on their combination with semantic technologies, shared data standards, and governance mechanisms, which are addressed in the following sections.

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.

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.1. 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 (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 4.1 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 4.1: 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	Data dashboards, automated compliance checks, regulatory

	example (discussed in more detail in section 6.5.2.3)	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 provide scalable storage and remote access capabilities.
- APIs 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. 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 (Zentraler Immobilien Ausschuss [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. 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).

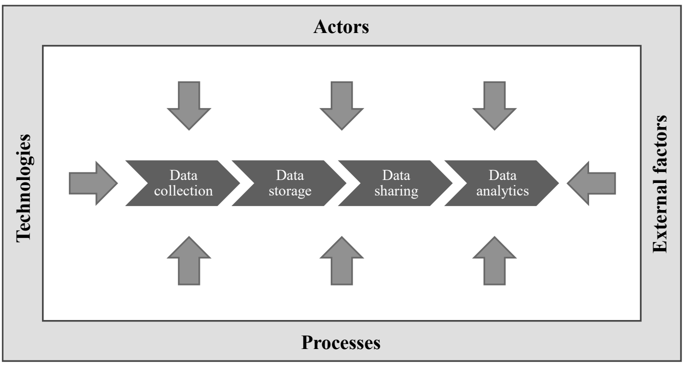


Figure 4.4: Overview on factors influencing building-related information management

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 4.2 provides an overview of the key categories in data quality management, explaining their role in maintaining high-quality data within BISs.

Table 4.2: 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 systematically analyzed to generate actionable insights tailored to the specific needs of different actors. Data analytics encompasses a broad range of approaches, including descriptive and diagnostic methods that support the understanding of current and past states, as well as predictive and prescriptive methods that anticipate future developments and support decision-making. These approaches draw on techniques from statistics, data mining, and machine learning and can be applied to heterogeneous data types such as time series, documents, images, and sensor data.

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). Additional evidence regarding data analytics use cases in the building life cycle is provided in the appendix (section C.2).

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. In the multi-actor environment and long-term perspective of BISs, security measures must ensure the confidentiality, integrity, and availability of data while supporting controlled access and system resilience throughout the building 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).

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. 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 (Eckert, 2018, p. 243), 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 (Hu, 2018, p. 14). 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 4.3).

Table 4.3: 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. 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. In BISs, data security is not a one-time technical configuration but an ongoing process that combines organizational, technical, and actor-related measures (DIN EN ISO /IEC 27001:2017-06; DIN EN ISO /IEC 27002:2024-01).

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. The following selection highlights important security aspects relevant to BISs. These aspects should be regarded as complementary to basic organizational and technical security measures commonly applied in information systems.

- 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 life cycle 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 (section 4.3.4), 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 (Eckert, 2018, p. 827; Hansen et al., 2019, p. 409).

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 4.4.

Table 4.4: 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). Together, these elements form a consolidated requirement profile, which is summarized in section 5.7 and operationalized in a fact sheet format.

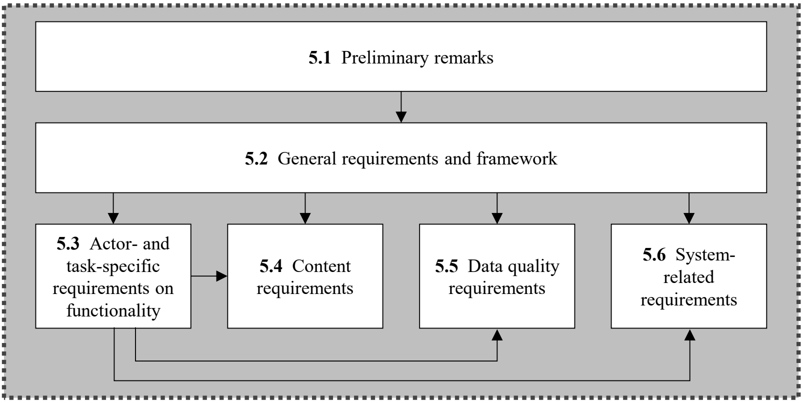


Figure 5.1: Structure of chapter 5

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).

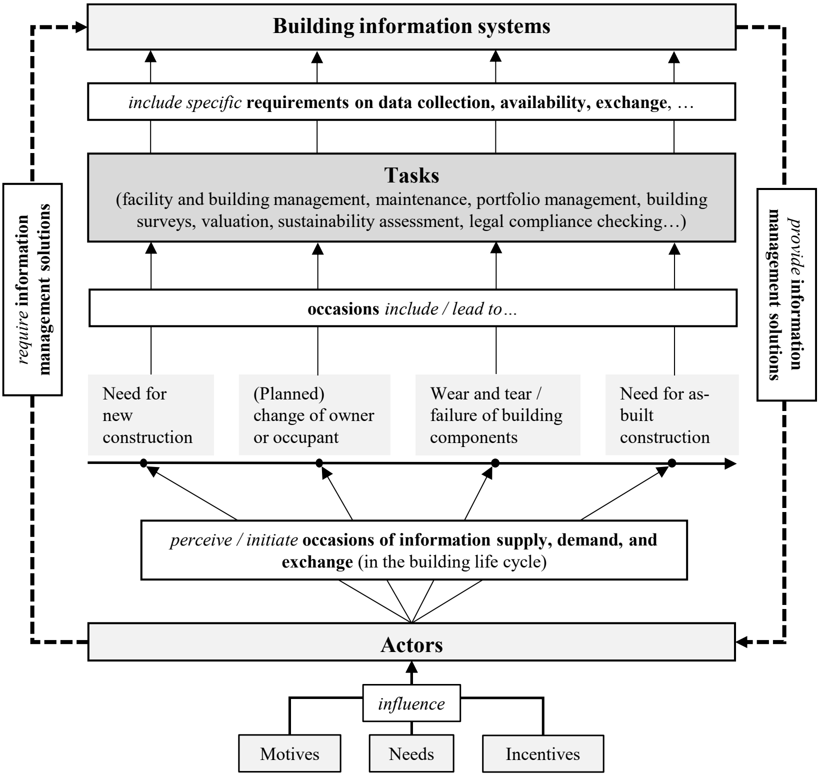


Figure 5.2: Role of building information systems in the context of life cycle information management (Buchholz & Lützkendorf, 2024, p. 3)

According to its definition (section 2.2.3), 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 2.2.3). 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 overarching objective of a LC-BIS is to support real estate management by improving information management practices. At the level of individual buildings, this includes enabling informed decisions related to sustainability objectives, such as limiting environmental and climate-related impacts, or preserving asset value over time. When applied at the level of building portfolios or entire building stocks, the potential benefits increase further, as consistent and comparable data can support strategic decision-making, transparency, and the reduction of information gaps and asymmetries.

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. The object of consideration is defined by the properties and attributes of a specific building, framed as "building-related data" as defined in section 3.1. The scope of building-related data maintained in a LC-BIS must be clearly defined in order to specify system functionality and to distinguish LC-BISs from other types of building information systems.

An LC-BIS should not be restricted to specific building use types but must be applicable to both residential and non-residential buildings. Differences in data scope, level of detail, and update frequency may arise depending on building type, size, and complexity. The system must therefore be adaptable with respect to data granularity and functionality, while maintaining a consistent overall structure.

In cases where buildings involve multiple owners or differentiated responsibilities, the LC-BIS must support a clear delineation of the object of consideration and associated data responsibilities. While the system may address the building as a whole, it must also be capable of distinguishing between shared building components and privately assigned units. This differentiation is required to enable appropriate access rights, ensure data protection, and support decision-making processes at both individual and collective levels.

A defining requirement of a LC-BIS is the integration of a life cycle perspective that extends across all stages of a building's existence. These stages range from planning and design through construction, operation, renovation, and deconstruction or demolition (section 2.1.2). The LC-BIS must therefore be capable of managing building-related data in a manner that ensures their relevance, accessibility, and usability throughout the entire life cycle.

To support life cycle-oriented information management, a LC-BIS must systematically relate building-related data to time. This includes

- documenting the time of data creation or collection,
- defining periods of validity in relation to specific life cycle contexts, and
- maintaining version histories to reflect changes over time.

Temporal referencing is particularly important for tasks such as permitting, renovation planning, and building documentation, where data validity and consistency are critical.

The scope of a LC-BIS must further accommodate the diverse actors and tasks involved throughout the building life cycle. This includes actors who create, manage, demand, or use building-related data, such as building owners, planners, contractors, real estate managers, and public authorities. The LC-BIS must support both time-specific tasks, such as permitting, handovers, maintenance, and refurbishments, as well as cross-cutting tasks that occur across multiple life cycle stages, including property valuation, risk management, marketing, and sustainability assessments and reporting.

5.2.2 Requirements on core functions

The core functions of a life cycle building information system (LC-BIS) derive from its overarching purpose of supporting building-related information management and, more specifically, the management of building-related data. To fulfill this purpose, a LC-BIS must primarily function as a life cycle-oriented data repository that enables the reliable provision of building-related data for actors and their tasks.

In its role as a data repository, a LC-BIS must enable actors to add, retrieve, and update building-related data in a structured manner. These functions correspond to the fundamental operations of writing, reading, and modifying data. The LC-BIS must provide controlled access to data when required, thereby supporting task-specific information demand throughout the building life cycle. By integrating building-related data from diverse sources, the LC-BIS should serve as a single source of truth, increasing data reliability and trust among actors.

A defining functional requirement of a LC-BIS is the facilitation of consistent data collection and storage across all life cycle stages ("*durchgängige Datenhaltung*"). This continuity is essential to reduce information loss and media discontinuities, which frequently occur at life cycle transitions and during handovers between actors. To support these processes, the LC-BIS must organize building-related data in a systematic and comprehensible way, potentially supported by a data model and appropriate ICT infrastructure. While a LC-BIS is not necessarily a dedicated data quality management system, its structured organization of data and defined processes can substantially contribute to maintaining data quality.

Beyond its repository function, a LC-BIS must support the systematic documentation of building-related information. In this role, the system facilitates the structured collection of data at defined occasions throughout the building life cycle, such as planning documentation, construction records, maintenance activities, and transactions. To be effective, this documentation function requires clear specifications regarding data formats and quality expectations, ensuring that relevant information is consistently captured and reusable for subsequent tasks.

By enabling controlled access to shared data, the core functions of a LC-BIS inherently support data sharing among actors. As a minimum requirement, the system must facilitate structured information exchange and collaboration based on shared data resources. Depending on the implementation, a LC-BIS may additionally support real-time communication between actors; however, such capabilities are not a prerequisite for fulfilling its core functions.

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 fulfilling these core functions, a LC-BIS contributes to decision-making, administration, and knowledge management for building-related tasks throughout the life cycle. Building on this foundation, LC-BISs may evolve to include extended functions that enhance their analytical and decision-support capabilities. These extended functions are not essential prerequisites but represent optional developments that depend on system maturity, organizational needs, and available data quality. Examples include:

- *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.

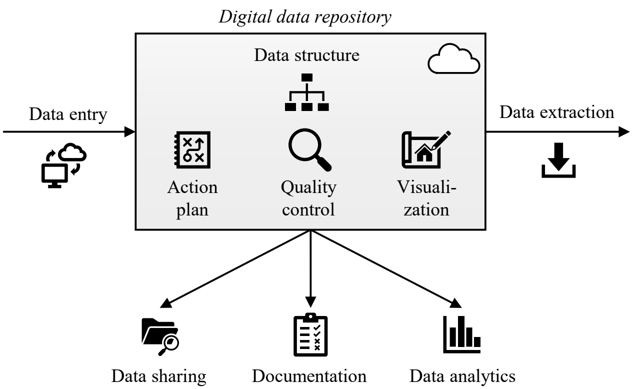


Figure 5.3: Core functions and extended function of life cycle building information systems

The functions described in this section will be considered in the specification of actor-specific requirements (section 5.3).

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:

- 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.
- 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 must support actors in performing tasks that arise at different stages of a building's life cycle. Functional requirements therefore vary depending on the timing, purpose, and organizational context of these tasks. To remain effective, a LC-BIS must adapt its functionality to changing information management needs while maintaining continuity of data availability and usability across stages (Figure 5.4).

During the early life cycle stages, including planning and construction, information management is characterized by intensive data creation and documentation activities. At the same time, data collection is often perceived as an additional burden within project-based workflows. A LC-BIS must therefore support streamlined and structured documentation processes that integrate smoothly into existing workflows. This includes providing clear guidance on how information is to be recorded, supporting standardized handovers, and reducing redundant documentation efforts. Interoperability with other information systems used during these stages, such as planning, project management, or modeling tools, is a key functional requirement to avoid inefficiencies and information loss. In fulfilling these functions, the LC-BIS contributes to establishing a reliable information basis for subsequent life cycle stages.

Once a building enters the use phase, the functional focus of a LC-BIS shifts toward ensuring efficient access to information, supporting collaboration between actors, and enabling informed decision-making. Tasks related to operation, maintenance, and refurbishment planning require that relevant information remains accessible, comprehensible, and up to date over long periods of time. A LC-BIS must therefore support task-specific access to information for different actor groups, such as portfolio, asset, and facility managers, while accommodating varying levels of technical expertise and organizational capacity. Advanced functional capabilities, such as data aggregation, visualization, and automation, may be required to support complex decision-making processes, whereas simpler use cases may prioritize ease of use and intuitive system navigation. Functional flexibility is thus a key requirement to address heterogeneous user needs.

At later stages of the building life cycle, including major renovations, changes of use, or deconstruction, the LC-BIS must ensure that historically collected information remains available and interpretable. Functional requirements at these stages include the ability to retrieve and contextualize information that was created under different conditions and by different actors. By preserving continuity in information management, a LC-BIS supports planning, compliance, and decision-making processes that depend on long-term documentation.

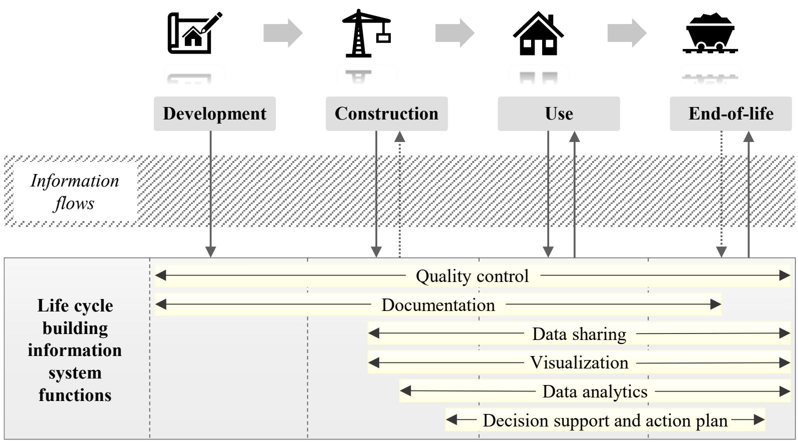


Figure 5.4: Relevance of life cycle building information systems functions throughout the building life cycle

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 places specific functional requirements on LC-BISs due to its roles as building owner, developer, regulator, and policymaker. In these capacities, public authorities depend on structured and reliable building-related information to support administrative, strategic, and regulatory tasks.

A LC-BIS must enable the provision of standardized and comparable building-related data that can support statistical analyses and monitoring activities at municipal, regional, or national levels. This includes facilitating access to information relevant for building stock assessments, energy performance monitoring, and housing-related analyses. By providing structured and interoperable data, a LC-BIS can reduce the effort associated with fragmented surveys and decentralized data collection, thereby supporting more efficient public data management processes.

In its regulatory function, the public sector requires digital support for administrative procedures such as building permitting, compliance verification, and certification processes. A LC-BIS must therefore be capable of integrating with digital administrative workflows and enabling the standardized exchange of relevant information between private actors and public authorities. Structured data formats and interoperable interfaces are essential to support such processes and to enhance transparency and traceability.

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. 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 3.3.7.2). 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 require not only raw data but also processed information that supports interpretation and action. A LC-BIS must therefore accommodate processed data derived from raw building-related data or external sources.

Processed data primarily include indicators and evaluation results that condense complex information into usable metrics, such as environmental, financial, or performance-related indicators. These enable actors to assess technical quality, sustainability performance, or economic conditions in a structured and comparable manner. The reliability of such indicators depends on the availability and quality of underlying raw data, which form the basis for meaningful analysis.

Beyond indicators, processed data may also include outputs generated through analytical functions, such as structured recommendations or action proposals. These can support strategic and operational tasks, for example in asset management, building operation, or renovation planning. The scope and complexity of such processed data depend on the functional maturity of the LC-BIS and the availability of high-quality input data.

5.4.1.3 Documents and files

Documents and files remain a central component of building-related information management. A LC-BIS must therefore support both structured data and document-based information formats.

While structured data enable efficient processing, analysis, and interoperability, many actors continue to rely on documents such as reports, contracts, certificates, or manuals. The LC-BIS must accommodate these formats and ensure consistency between granular data entries and associated documents. This includes enabling the generation of documents from structured data as well as the extraction or referencing of relevant information contained in documents.

Documents arise throughout the building life cycle and serve as important carriers of contractual, technical, and regulatory information. The LC-BIS must therefore support the storage, organization, and controlled access to such documents in alignment with its broader data management structure.

Table 5.3 provides an overview of relevant document types across different life cycle stages.

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 integrating structured data and document-based information within a coherent framework, a LC-BIS ensures that diverse user needs can be addressed without compromising data consistency or usability.

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 3.3.7, while a comprehensive list can be found in section B.5. 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, reusability, unique identification	Standardized data formats and structures should be applied to ensure compatibility with other systems, enable data reuse, and support seamless 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

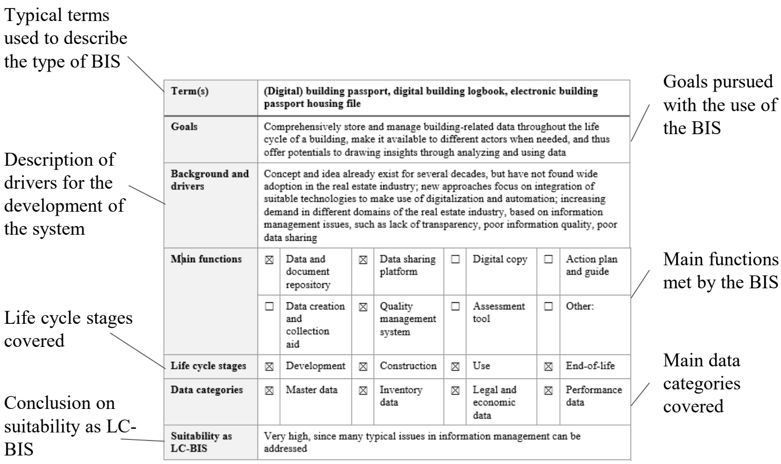
Several insightful aspects were outlined in this section to stress critical aspects that must be considered for a LC-BIS.

- 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).



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.

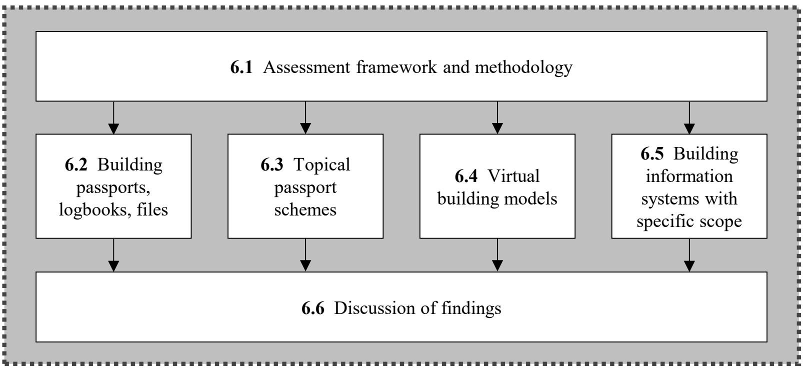


Figure 6.1: Structure of chapter 6

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.

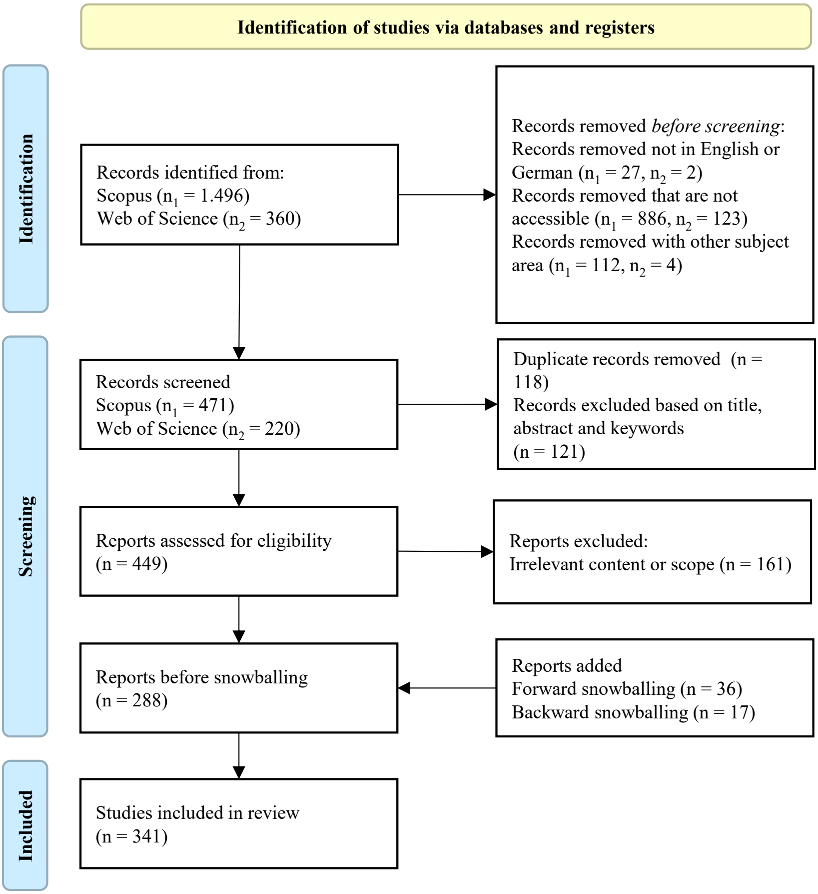


Figure 6.3: Steps of the systematic literature review based on Page et al. (2021)

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.

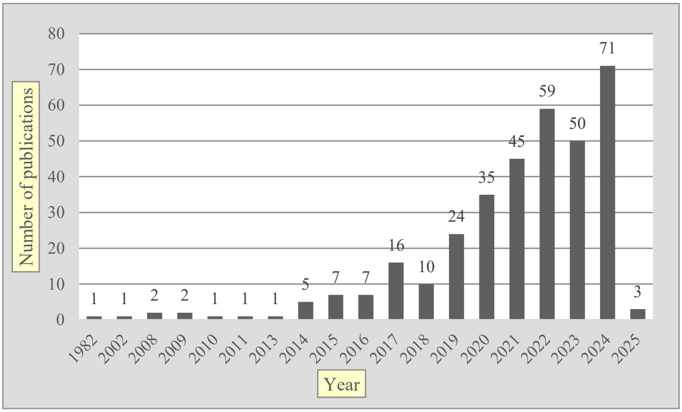


Figure 6.4: Number of publications identified in the review per year

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.

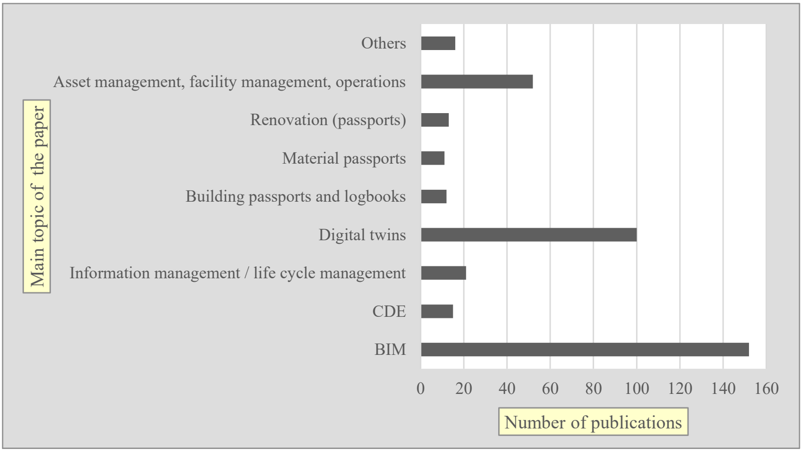


Figure 6.5: Main topics of the papers identified in the literature review

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. 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.1.1). 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.1.2). 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.1.3) 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).

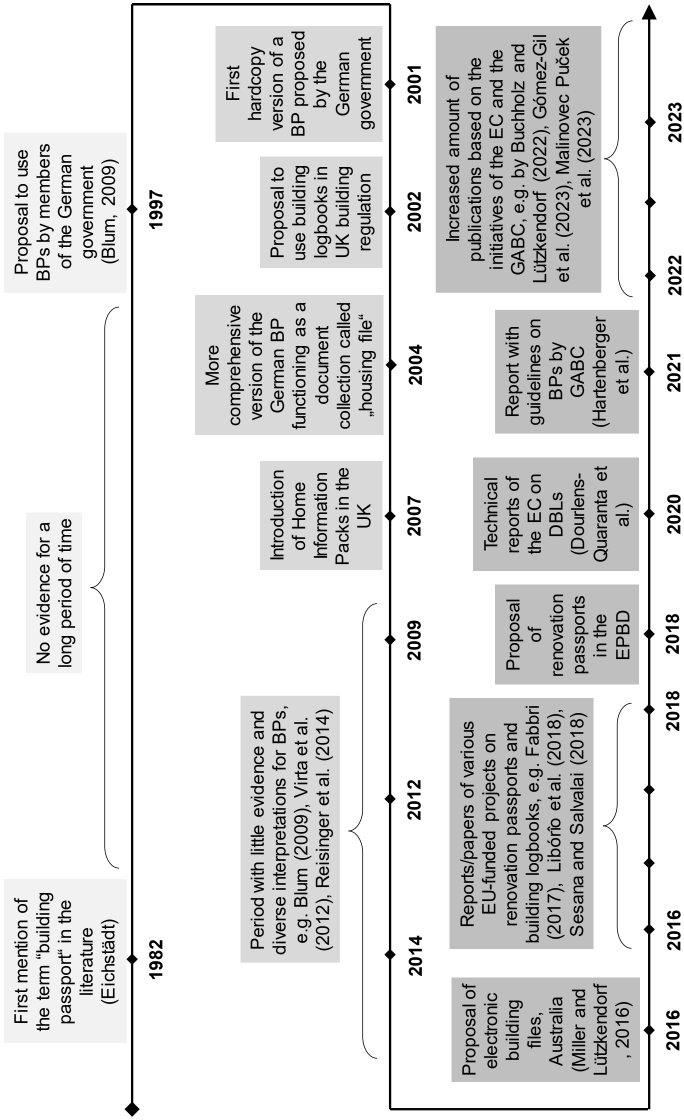


Figure 6.6: Milestones of building passport / logbook development (Buchholz & Lützkendorf, 2023, p. 909)

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.1.4 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 E.1.5 (policy initiatives) and E.1.6 (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 (2022, 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 (2022), 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 (1998, pp. 180–181) and in the official proposals for a building passport (section E.1.1) and a housing file (section E.1.2).

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, 2022, 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.1.7. 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, 2022, 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, 2022, 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).

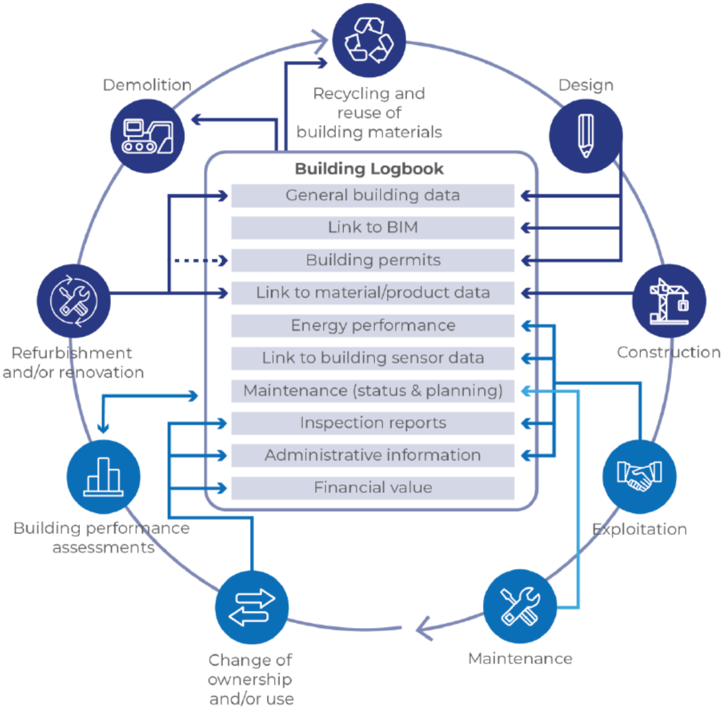


Figure 6.7: Life cycle coverage of digital building logbooks in connection with relevant data categories (EC, 2023, p. 11)

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, 2025). 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

Term(s)	**Building renovation passport, renovation roadmap, decarbonization roadmap, climate roadmap**							
Goals	Collecting and managing building-related data that are necessary for making profound renovation decisions in the long term							
Background and drivers	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;							
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	Limited suitability, when only used in the context of a roadmap; synergies and job-sharing with LC-BISs possible							

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).

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 constitutes a methodology that includes processes of creating, modeling, and visualizing of building-related information with the help of technological and managerial components. It has evolved from basic 2D/3D representations to multidimensional models that integrate time, cost, facility management, and sustainability aspects. 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, platforms, servers, and environments. Digital twins build on the foundations of digitized building models to enable real-time monitoring, simulation, and predictive analytics (Boje et al., 2020, p. 8; Hosamo et al., 2022, p. 13).

There is a wide body of literature that examines the further development and trends in leveraging virtual building models for information management. Table 6.6 provides an overview of these trends.

Table 6.6: Overview on current trends in applying virtual building models to information management throughout the building life cycle

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 (Hemmerling & Bähre, 2020, pp. 59–60)
Building Life-cycle Management (BLM)	Extends BIM applications to support all building phases, from design through construction to deconstruction, ensuring continuous, up-to-date information (Di Biccari et al., 2018, p. 69)
Collaborative BIM	Integrates multi-stakeholder workflows within shared BIM environments, streamlining data exchange and coordination (Beach et al., 2017, p. 1)
BIM for facility management and As-built BIM	Transitions design models into dynamic as-built models that support facility management through updated, operational data (He et al., 2017, p. 680)
BIM for deconstruction	Applies BIM at the end-of-life stage to plan, simulate, and optimize deconstruction processes, facilitating recycling and waste reduction (Akinade et al., 2017, p. 267)
Common Data Environments (CDEs)	Employs centralized or federated platforms for storing, managing, and sharing building data, ensuring consistency and accessibility across the life cycle (DIN SPEC 91391-1:2019-04, p. 9)
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 (Boje et al., 2020, p. 1)

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).

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 approaches intend 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.

A key strength of virtual building models 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, 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 (Hemmerling & Bähre, 2020, p. 60).

BIM and digital twins also support advanced data analytics, enabling simulations, scenario analyses, performance assessments, and predictive modeling. These functions facilitate informed, data-driven decision-making and allow stakeholders to optimize performance, anticipate maintenance needs, and improve resource efficiency (Deng et al., 2021, p. 71).

Another core advantage is their support for integrated digital workflows. As discussed in the context of collaborative BIM, virtual building models enable real-time coordination across disciplines by replacing fragmented, tool-specific processes (Beach et al., 2017, p. 3). 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 can reduce redundancies, minimizes information loss, and improves consistency across stages and actors (Comiskey et al., 2017, p. 247).

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. 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 (Kassem et al., 2015, p. 263; Rogage & Greenwood, 2020, p. 471).

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, effective implementation presumes structured coordination, clearly defined roles, and governance mechanisms, all of which increase the entry threshold (Beach et al., 2017, p. 11).

Interoperability and data quality remain persistent issues (Schapke et al., 2018, p. 276). As seen with CDEs, 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 (Tchouanguem Djuedja et al., 2021, p. 14).

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, 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 connected to cultural barriers and it is particularly critical for actors with limited budgets or for projects without a strong digitalization mandate (Kassem et al., 2015, pp. 262–263).

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 3.3.4).

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 functions (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, BPs 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, 2022). 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).

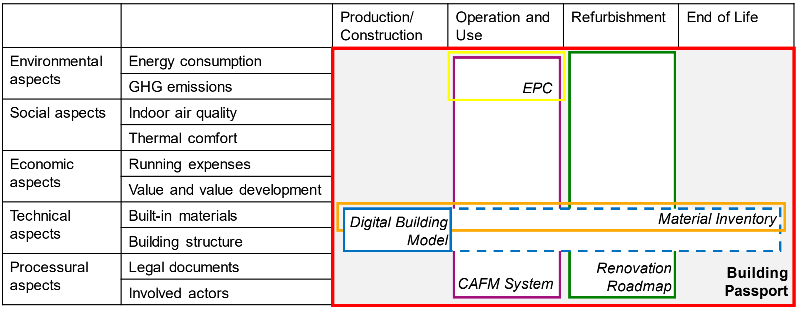


Figure 6.8: Data related focal points of selective building information systems throughout the life cycle (Buchholz & Lützkendorf, 2022, p. 6, 2023, p. 914)

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.

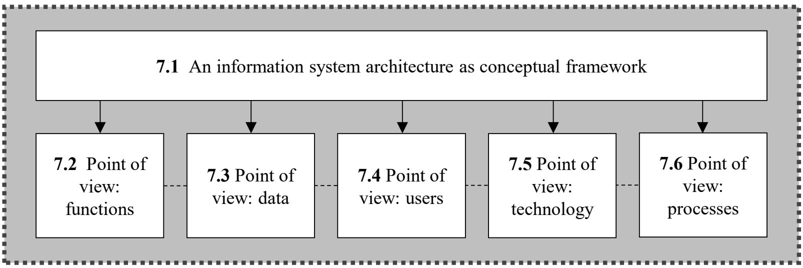


Figure 7.1: Structure of chapter 7

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 0). 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).

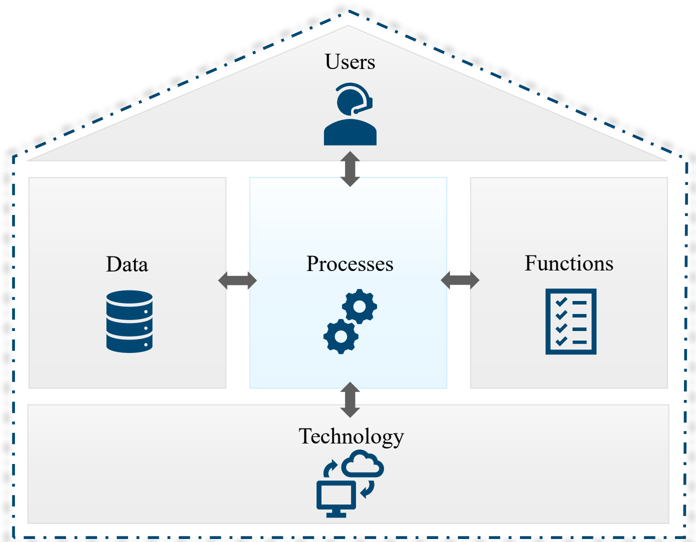


Figure 7.2: Information system architecture model for digital building passports based on Buchholz and Lützkendorf (2024, p. 6)

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 2.2.2.2). 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 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 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 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.

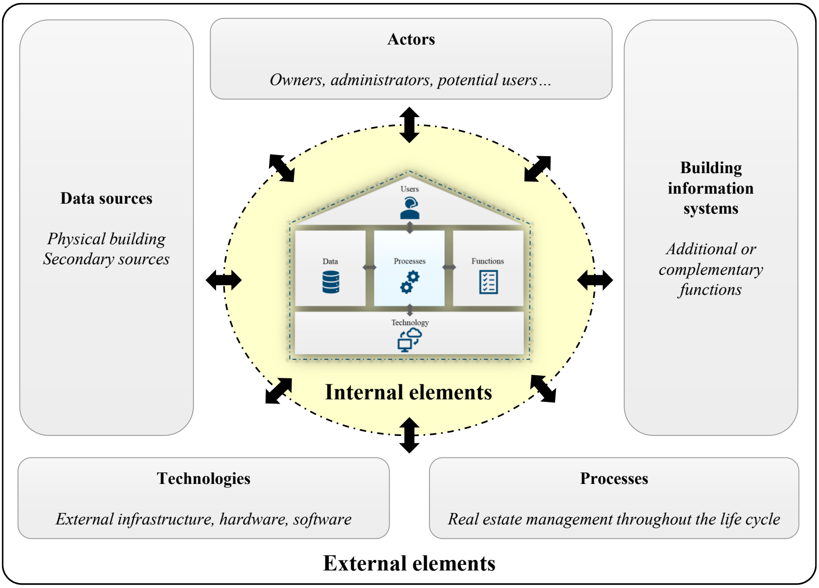


Figure 7.3: Overview on system boundaries for digital building passports

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.

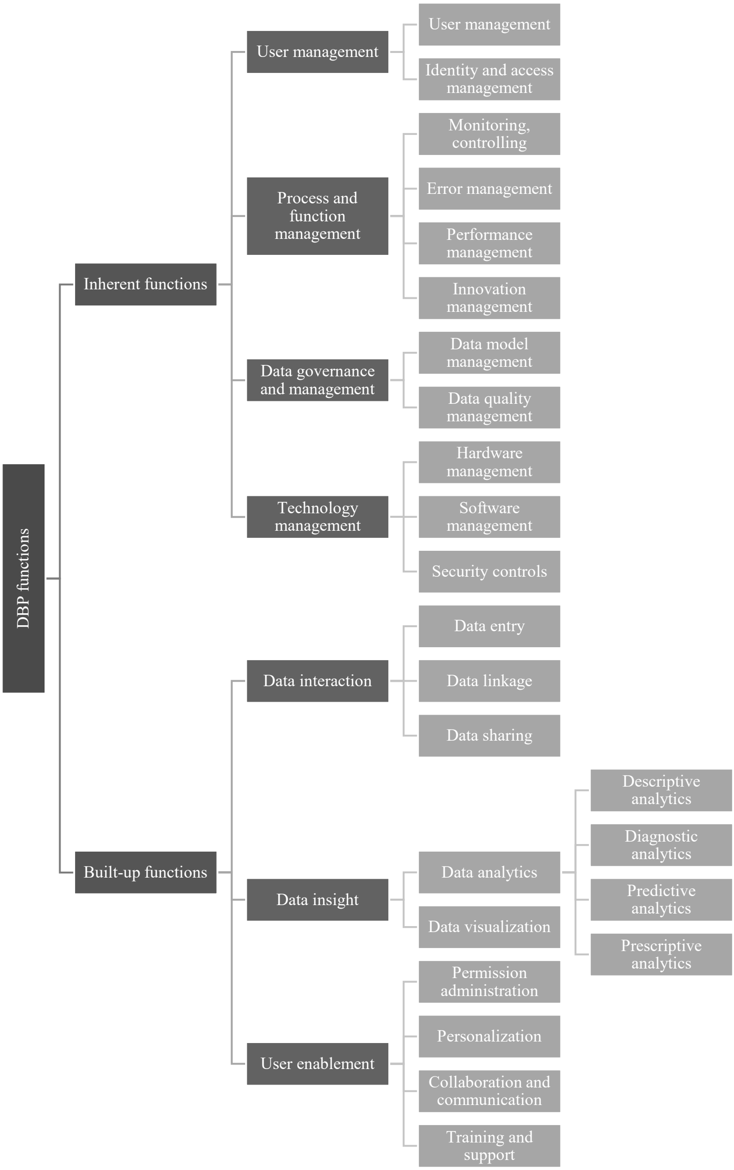


Figure 7.4: Function tree for digital building passports based on Buchholz and Lützkendorf (2024, p. 9)

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 7.3 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 vary significantly in quality.

These characteristics directly imply specific design requirements for the data element of the ISA. It must enable multi-perspective representations without creating redundancies, represent both static attributes and dynamic processes, support hierarchical as well as cross-system relationships, allow aggregation and disaggregation across different levels of granularity, and accommodate distributed ownership and heterogeneous data quality. Without addressing these structural implications, a DBP would risk fragmentation, inconsistencies, and limited usability across life cycle stages and actors.

To operationalize these requirements, the data element of the ISA is structured around two tightly connected components: a *data model* and an overarching *data architecture*. The data model defines the structure, relationships, and semantics of building-related data, while the data architecture organizes specifications, identifiers, and metadata to ensure consistent handling, traceability, and interoperability. Together, they establish the structural backbone that enables accessibility, quality assurance, and long-term usability across use cases.

Within the data element of the ISA, architectural components such as metadata structures, identification schemes, and specification management are closely linked to the selected data modeling approach. As outlined in section 4.2.2, the data structure encompasses essential elements that enable semantic clarity and interoperability. While data architecture and data model can be conceptually distinguished, the chosen modeling paradigm substantially influences how architectural elements are formalized and implemented in practice. For example, ontology-based approaches inherently support formal semantics and identifier management, whereas schema-based approaches require more explicit structural definitions. For this reason, architectural implications are considered in conjunction with the evaluation of data modeling approaches (section 7.3.3).

The ISA defines the conceptual requirements and structural principles of the data element. Detailed technical implementation choices, including specific tools, platforms, or deployment strategies, remain application-specific and are therefore beyond the scope of this section. A more detailed explanation of core architectural components in the context of DBPs and 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 defines the functional scope of the data element within the ISA, as it determines which life cycle tasks can be supported and which actor requirements can be fulfilled. 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. Within the ISA, the taxonomy serves as a structural baseline for organizing data content, while remaining open to extensions where specific use cases require additional differentiation.

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.5). These provide a foundational overview, ensuring clarity on why certain data are essential and how they align with the overarching goals of LC-BISs.

7.3.3 Data modeling approaches

A DBP could, in its simplest form, function without a formalized data model and act as a static repository for unstructured or semi-structured documents such as PDFs or spreadsheets. However, this approach has severe limitations. Without a data model, data representation would be inconsistent, interoperability with other systems would be limited, and efficient data management would require considerable manual effort. These constraints render 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; Supports hierarchical relationships that reflect real-world building structures; Well-suited for predefined and stable data categories	Limited ability to represent complex, cross-cutting relationships; Lacks semantic richness, making interoperability and data integration challenging; Does not inherently support extensibility for evolving data needs
Ontology-based semantic modeling	High level of semantic data interoperability; Well-suited for (knowledge) graphs; Strong basis for data analytics (e.g., AI applications); Independent of physical data modeling and storage;	Matching different ontologies can be challenging; Broader scope may result in less detailed properties; Difficult to represent building geometries effectively

	Can represent semi-structured and unstructured data	
Combination of ontologies and data dictionaries	Standardizes terms and concepts; Leverages the strengths of ontology-based approaches; Enhances semantic clarity while maintaining operational focus	Inherits weaknesses of ontology-based approaches; 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; Provides unambiguous formalization through schemas and formats; Well-suited for structured data and hierarchical relationships	Reduced interoperability with systems using different schemas; High manual effort for updates or schema changes; Changes to the physical level can introduce inconsistencies; Not suitable for unstructured data
Schema-based modeling with IFC	Established domain standard for interoperability; Rich semantic modeling of building-related data, including geometry and relationships; Broad industry adoption; Compatibility with BIM tools and workflows	Complexity of schema makes implementation challenging; Limited flexibility for use cases beyond the BIM domain; 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.

Overall, ontology-based approaches, particularly when combined with standardized data dictionaries, demonstrate strong potential to address requirements related to semantic clarity, interoperability, and adaptability. Their suitability for linked data environments and distributed data integration further strengthens their relevance in the DBP context. At the same time, schema-based approaches such as IFC provide robust solutions for geometry-intensive and BIM-centered applications, while more hierarchical structures may suffice for limited and well-defined use cases. The comparative analysis thus indicates that the underlying modeling paradigm significantly shapes the achievable level of semantic richness, integration capability, and long-term flexibility within a DBP environment.

7.3.4 Design implications

The comparative assessment of data modeling approaches illustrates that no single paradigm fully satisfies all potential requirements of DBPs. However, clear implications for the data element of the ISA can be derived from the evaluation and from the requirement profile established in chapter 5.

First, the ISA does not prescribe a specific data modeling standard. Instead, it defines structural and qualitative requirements that a chosen modeling approach must fulfill. These include semantic clarity, interoperability across heterogeneous systems, extensibility for evolving data needs, and the capability to integrate distributed data sources across life cycle stages and actors.

Second, modeling approaches that support explicit semantics and flexible integration mechanisms are particularly well aligned with these requirements. Ontology-based approaches, especially when combined with standardized data dictionaries, offer significant advantages in multi-stakeholder environments where interoperability and long-term adaptability are essential. At the same time, schema-based approaches such as IFC remain highly relevant for use cases requiring detailed representations of building geometry and established BIM workflows. For contexts with limited complexity and lower interoperability demands, hierarchical or taxonomy-based structures may provide a sufficient and pragmatic solution.

Third, the selection of a data modeling approach must follow the defined data content requirements rather than precede them. The ISA therefore positions the modeling paradigm as a realization decision guided by functional scope and quality requirements, not as a predetermined technological constraint.

In summary, the ISA adopts a requirement-driven and model-agnostic stance: it establishes the structural principles that the data element must satisfy while leaving the concrete modeling implementation adaptable to specific application contexts. This ensures both architectural consistency and flexibility for diverse DBP use cases.

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.

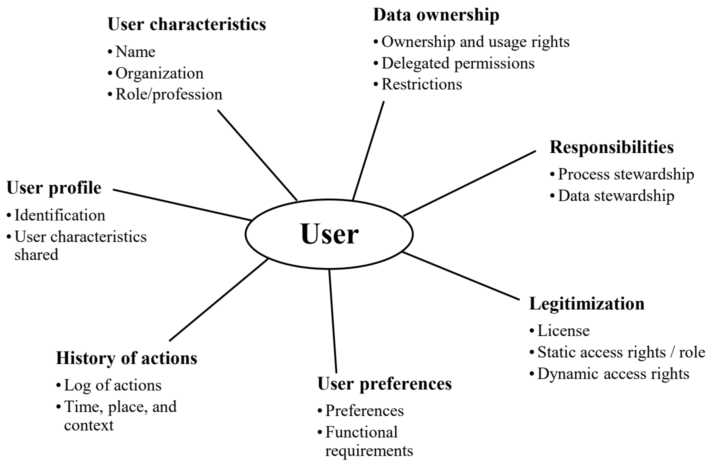


Figure 7.5: User model for digital building passports based on Buchholz and Lützkendorf (2024, p. 7)

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 stew-ard	(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).

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 perspective within the ISA conceptualizes ICT as the enabling infrastructure that operationalizes the functions defined in the preceding system elements. ICT constitutes the non-human component of DBPs and provides the technical means through which data are collected, processed, stored, secured, and exchanged across the building life cycle. Technology is therefore not an independent design driver but an instrumental layer derived from functional and structural system requirements.

The identification of relevant ICT components follows from the function bundles defined in section 7.2, particularly those related to data management, interoperability, automation, and governance. In this context, a distinction can be made between core technologies, which ensure basic system operability, and additional technologies, which extend capabilities through automation, advanced analytics, or enhanced interoperability.

System requirements such as availability, scalability, efficiency, configurability, and security constrain and guide technological selection. For example, availability may require distributed and fault-tolerant infrastructures; scalability may favor modular architectures; efficiency may justify automation and AI-supported processing; and interoperability may necessitate standardized interfaces and semantic models. The technological layer thus reflects the operational translation of the requirement profile rather than an independent technological agenda.

The technologies discussed in this section are conceptual options derived from current technical potentials and system requirements. Their inclusion does not imply a prescriptive implementation path. Technological neutrality remains essential to preserve interoperability, long-term adaptability, and vendor independence. Accordingly, technology selection must remain requirement-driven: ICT serves the functional objectives of DBPs, not vice versa.

7.5.2 Core technologies

7.5.2.1 Information infrastructure

The feasibility of DBPs depends on the availability of basic information infrastructure. Although such infrastructure is often taken for granted in highly industrialized contexts, it constitutes a fundamental boundary condition for implementation in a global perspective.

At minimum, DBPs require reliable electricity supply, stable telecommunication networks, and internet connectivity to enable digital data storage, exchange, and multi-actor access. Without these prerequisites, core system functions, such as structured data management and distributed accessibility, cannot be ensured.

In addition to critical infrastructure, access to adequate hardware, including computers and mobile devices, is necessary for system interaction and data input. Depending on the scope of implementation, further technical equipment may support data acquisition, but this is not a prerequisite for basic DBP operability.

Infrastructure availability should therefore be considered an external enabling condition when assessing the feasibility and scalability of DBPs across different regional and economic contexts.

7.5.2.2 Cloud architecture

The proposed three-layer architecture, comprising presentation, application, and data management layers, provides the structural foundation for DBP implementation. Its relevance lies not in the architectural model itself, which is well established in software engineering, but in its suitability for supporting modularity, scalability, and separation of responsibilities within a multi-actor data environment.

Separation of concerns is particularly important for DBPs, as user interaction, functional logic, and data persistence must remain independently adaptable.

- The presentation layer enables user access across devices and actor groups without affecting underlying system logic.
- The application layer operationalizes DBP functions through modular components, allowing functional extensions without structural redesign.
- The data management layer ensures structured storage and controlled access to building-related information, translating conceptual and semantic models into logical and physical database structures.

Cloud-based deployment strengthens this architecture by enabling distributed accessibility, elastic resource allocation, and reduced dependency on local infrastructure. For DBPs, which are designed to support decentralized data ownership and cross-organizational interaction, cloud infrastructure provides the flexibility necessary to accommodate heterogeneous users and evolving functional requirements.

Low-code or cloud development platforms may facilitate implementation by reducing development complexity; however, their use remains optional and must align with long-term interoperability and maintainability considerations.

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). 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).
- *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.

Data security constitutes a foundational requirement of DBP architecture, as the system manages sensitive technical, financial, and potentially personal information across multiple actors and life-cycle stages. Security must therefore be embedded across all architectural layers rather than treated as an isolated technical add-on.

The following mechanisms are essential:

- Access control: RBAC/ABAC models regulate permissions according to actor responsibilities (section 7.4.3). This ensures controlled interaction with data while supporting differentiated stakeholder involvement.
- Encryption: Data must be protected both at rest and in transit to safeguard confidentiality during storage and exchange.
- Secure development practices: Implementation must follow secure coding standards and include regular vulnerability assessments to mitigate risks typical of web-based and distributed systems.
- Backup and recovery: Regular and geographically distributed backups are necessary to preserve data integrity and system continuity. Immutable logging mechanisms, potentially supported by blockchain technologies (section 7.5.3.3), may enhance traceability for critical records.
- Audit and monitoring: Continuous logging and anomaly detection mechanisms are required to ensure transparency, detect unauthorized activities, and maintain accountability across actors.

These measures collectively ensure that DBPs meet fundamental requirements of integrity, confidentiality, availability, and traceability, thereby reinforcing system trustworthiness in a decentralized and collaborative environment.

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 provide an architectural approach that supports functional modularization within DBPs. By decomposing system functionality into independently deployable services, DBP components can evolve incrementally without requiring structural redesign of the overall system.

This approach is particularly relevant where DBPs must accommodate heterogeneous use cases, actor groups, and regulatory contexts. Individual services, for example, analytics modules or automated assessment functions, can be extended, replaced, or scaled independently, enabling adaptive system development while preserving architectural stability.

Containerization technologies further enhance this modular structure by abstracting services from underlying infrastructure. This facilitates deployment across different cloud environments and supports elastic scaling in response to varying usage demands. However, the adoption of microservices should be proportionate to system complexity, as smaller or highly centralized DBP implementations may not require this level of architectural granularity.

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 may support the integration of legacy, unstructured, or heterogeneous building-related data into DBPs. In particular, machine learning and computer vision techniques can automate the extraction, classification, and transformation of information from scanned documents, plans, or other non-structured sources. This reduces manual processing effort when incorporating historical or externally generated data into the system.

While primary data acquisition methods such as laser scanning or surveying lie outside the functional scope of DBPs, AI can facilitate the preprocessing and structuring of such data once available. In this sense, AI acts as an enabling layer that supports the translation of externally generated datasets into DBP-compatible formats.

For sensor-based data originating from building automation or monitoring systems, AI may assist in filtering, structuring, and validating incoming data streams before integration. The relevance of AI for data collection therefore depends on the heterogeneity and quality of existing data sources. Its use should be proportionate to the complexity of integration tasks rather than treated as a universal requirement.

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

The effectiveness of DBPs does not derive from individual technologies in isolation, but from their structured integration within a coherent architectural framework. Core technologies establish the operational foundation required for data storage, access, and security, while additional technologies selectively extend interoperability, automation, and analytical capabilities.

The combination of technologies must remain guided by functional requirements and system objectives. Different implementation contexts may justify different configurations, depending on factors such as system openness, actor diversity, data complexity, and governance structures. Consequently, DBP architectures should be conceived as modular and scalable arrangements of technological components rather than as fixed technical solutions.

Figure 7.6 synthesizes the relevant ICT components within the proposed three-layer architecture. It illustrates how core and additional technologies can be positioned relative to presentation, application, and data management layers, thereby enabling structured yet adaptable implementation strategies.

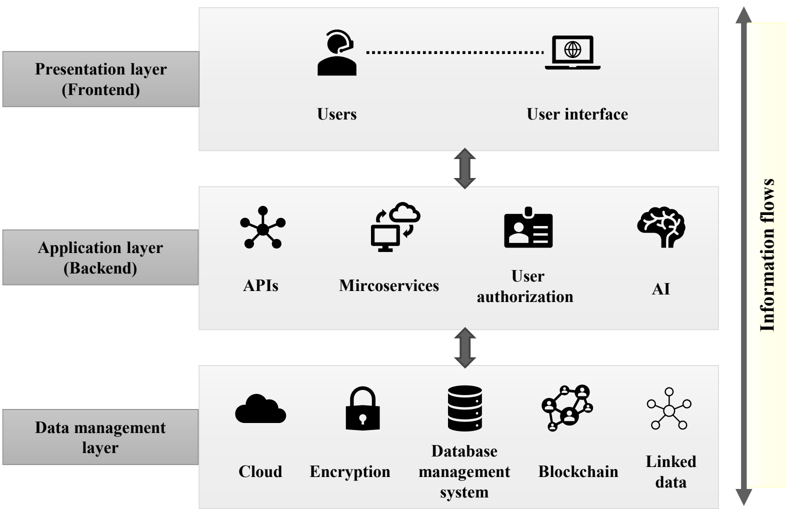


Figure 7.6: Overview on relevant technologies for digital building passports

7.6 Point of view: processes

7.6.1 Derivation and assumptions

The process element constitutes the integrative core of the ISA, dynamically linking the otherwise static elements of function, user, data, and technology within a coherent operational framework. Unlike these structural perspectives, the process view introduces the temporal dimension, enabling the controlled flow of resources, primarily information, across system elements and between the system and its environment. Through this dynamic orchestration, DBPs operate as adaptive and context-sensitive information systems. Three categories of flows characterize the process element:

- Information flows between ISA elements: Bidirectional flows connect users, data, functions, and technology within structured workflows. Processes not only operationalize these elements but also enable their continuous adjustment. In this way, changes in one element can propagate through the system via defined process logic.
- Internal flows organize procedural steps into a recurring life cycle of initialization, execution, and finalization. Initialization is triggered by defined internal events, such as user interaction or system status checks. During execution, functions are performed using available resources. Finalization concludes the specific process instance and resets the process logic for subsequent cycles. While static elements may be modified, the process structure itself remains cyclical and reversible.
- Flows between the DBP and its external environment: External flows regulate exchanges between the DBP and other information systems. These include the import and export of structured data, synchronization processes, and service-based interactions. Unlike user-triggered activities, these exchanges occur across defined system boundaries and require interface governance, semantic alignment, and technical interoperability mechanisms.

Taken together, these flow structures imply two fundamental architectural implications. First, the process element must ensure seamless internal integration by coordinating users, data, functions, and technology within coherent and consistently defined workflows. Second, it must regulate controlled external interaction by managing exchanges with other BISs across clearly defined system boundaries. Only through this dual coordination can the DBP operate as a coherent, scalable, and interoperable life-cycle-oriented information system.

7.6.2 Internal information flows

The ISA elements have so far been conceptualized as structurally distinct in order to reduce system complexity. The process view now reconnects these elements by specifying how they interact within operational workflows. Rather than treating the system as a set of isolated components, the focus shifts to their interdependencies and coordinated execution.

A structured way to approach this integration is to analyze binary relationships between two elements at a time before considering more complex multi-element interactions. Table 7.7 outlines central relations between ISA elements that require specification in the context of DBPs.

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 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

These binary relations form the foundation for more comprehensive workflows. For example, a user invoking a specific function may trigger data retrieval, processing through defined technologies, and the generation of structured outputs. Such interactions are not linear but interdependent, as changes in one element may affect others. The process element provides the coordinating logic that sequences these interactions and ensures consistency across system components.

As workflows become more differentiated, explicit process specification becomes necessary. A formalized process model enables consistent structuring of interactions, clarifies the contribution of individual ISA elements, and supports maintainability as the DBP evolves. The modeling approach used for this purpose is introduced in section 7.6.4.

7.6.3 Job-sharing possibilities for building information systems

To identify relevant information flows between DBPs and other BISs, clear system boundaries and functional distinctions must be established. Building on the neutral comparison developed in chapter 6, DBPs are positioned as LC-BISs with a defined scope of data, functions, users, and technologies. With the specification of the ISA, this positioning can now be operationalized in terms of interaction patterns.

Based on functional clustering, typical relations between DBPs and other BISs can be structured into four job-sharing approaches:

- Full integration: The DBP absorbs the functions and data of another BIS.
- Data integration: Building-related data are exchanged, shared, or linked across systems.
- Data provision: The DBP supplies structured building data to another BIS.
- Function provision: The DBP provides additional services, such as data quality management, analytics, or document generation.

The relations derived from this classification are summarized 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 appropriate job-sharing configuration depends not only on functional overlap but also on temporal positioning within the building life cycle. Information flows may therefore change direction over time. For example, real estate management systems may initially provide historical building data for

DBP setup. Once established as a structured repository, the DBP may become the primary source of validated information for downstream systems.

This dynamic illustrates the potential of DBPs to function as a central interface within a modular BIS ecosystem. Vertically, DBPs aggregate data from collection-oriented systems such as BAMSs and provide structured outputs to higher-level management tools. Horizontally, they may interconnect with systems that operate on similar data domains but emphasize different functions.

Virtual building models, including BIM-based applications and digital twins, represent a relevant horizontal counterpart. These systems offer advanced geometric visualization and computational capabilities but typically require specialized expertise and higher implementation effort. DBPs, in contrast, are designed for broader user groups and structured information accessibility. Interconnection through shared data models or APIs is therefore particularly relevant when both system types coexist. Under suitable user and governance conditions, deeper integration may be feasible.

Topical passport schemes, such as material or renovation passports, exhibit substantial data overlap with DBPs. In such cases, full integration may reduce administrative complexity and prevent redundant system operation. Where full consolidation is not feasible, at least interoperable data exchange should be ensured.

Figure 7.7 illustrates the positioning of DBPs within the BIS landscape and highlights potential vertical and horizontal integration pathways.

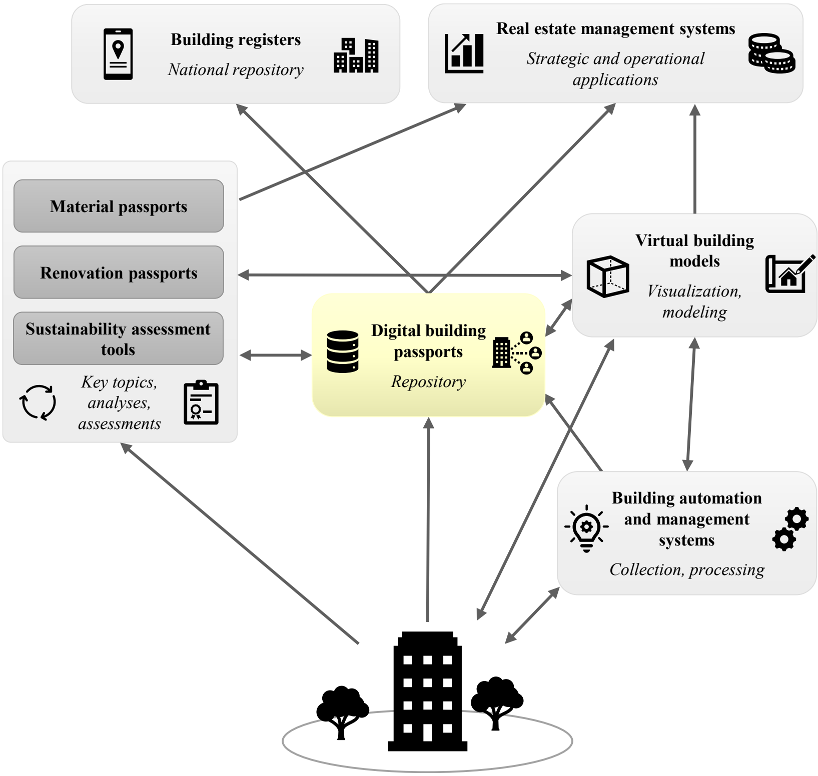


Figure 7.7: Ecosystem of building information systems including mutual interactions with digital building passports based on Buchholz and Lützkendorf (2024, p. 5)

To operationalize these job-sharing approaches, technical mechanisms are required. Data integration demands alignment of data models and metadata structures, supported by interface technologies such as APIs and Linked Data principles. Automation mechanisms, including AI-assisted data transformation and validation, can further facilitate interoperability. The technological foundations for such integration were discussed in section 7.5.

Through these coordinated interaction patterns, DBPs can function as structured integration nodes within a heterogeneous BIS environment.

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 2.3.3). 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. 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.

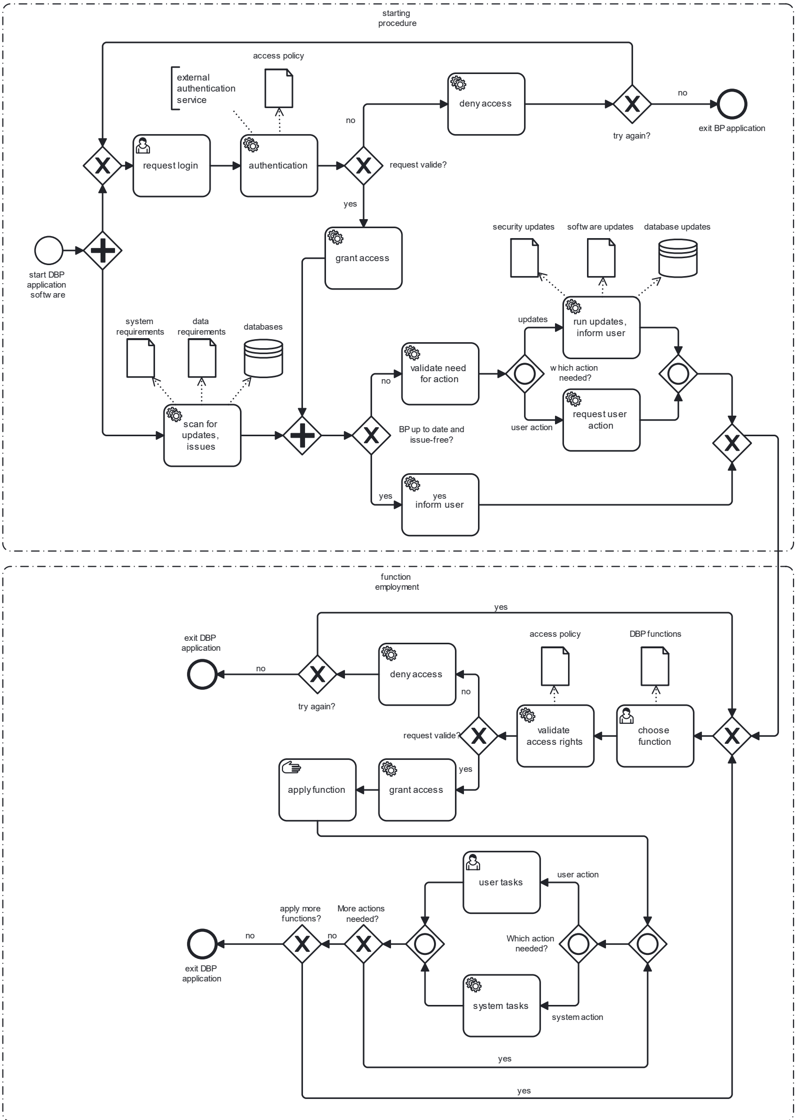


Figure 7.8: BPMN model for basic interaction with a digital building passport

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.

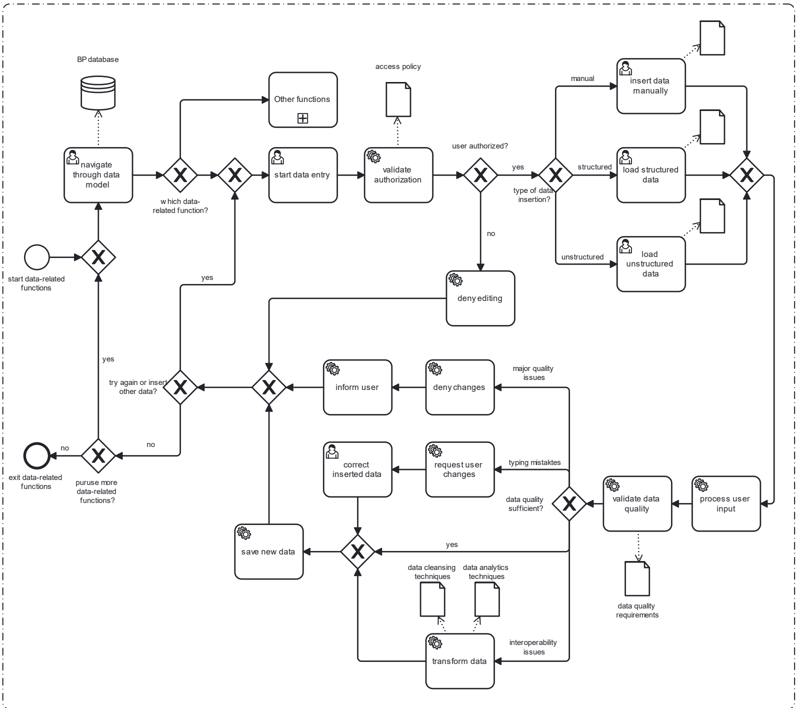


Figure 7.9: BPMN model for a data entry process in a DBP

7.6.7 Process model limitations

The proposed process model provides a conceptual framework for illustrating how the elements of a DBP interact within dynamic workflows. By abstracting from implementation detail, it supports structural clarity and facilitates the communication of core system logic. However, this level of abstraction necessarily limits its representational scope.

The model captures selected functions to demonstrate typical interaction patterns but does not reflect the full operational complexity of real-world DBP implementations. In practice, workflows are more differentiated, domain-specific, and influenced by heterogeneous data sources, diverse user roles, and evolving governance requirements. Furthermore, the model is based on predefined assumptions regarding user behavior, data quality standards, and system capabilities, which may vary across application contexts.

Despite these limitations, the model fulfills its intended purpose as a design-oriented reference structure. It provides a basis for iterative refinement and can be expanded as additional use cases, technical components, or regulatory requirements emerge. Its value therefore lies not in exhaustive representation, but in offering a coherent starting point for the structured development and operationalization of DBPs within heterogeneous BIS environments.

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.5) 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 0). 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).

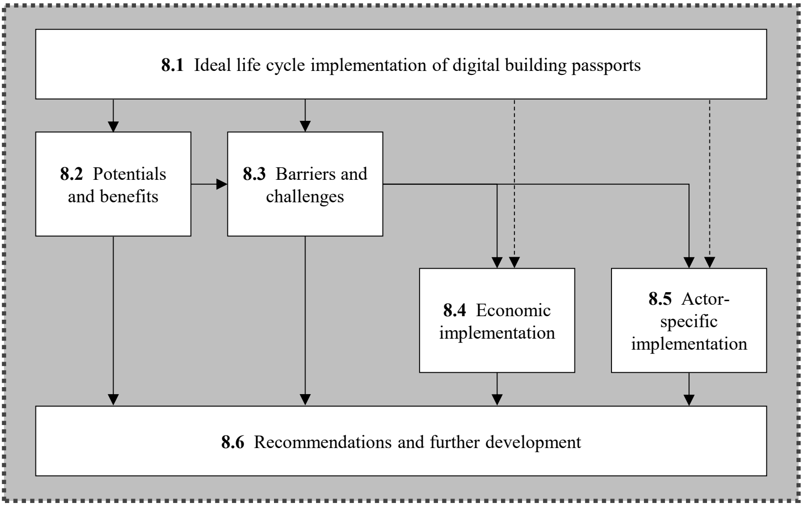


Figure 8.1: Structure of chapter 8

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 BISs

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.

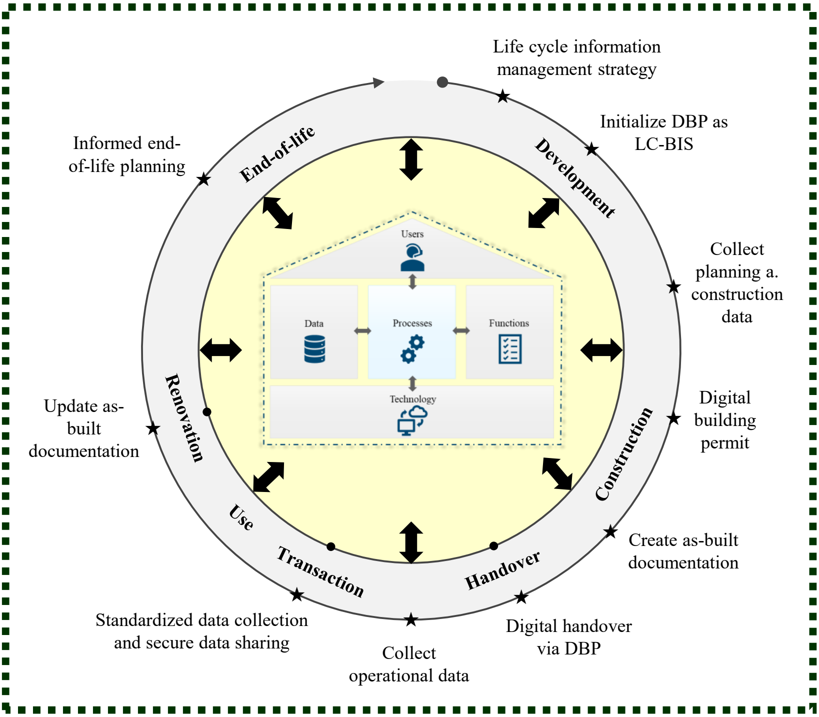


Figure 8.2: Milestones in implementing the digital building passport framework throughout the life cycle

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.

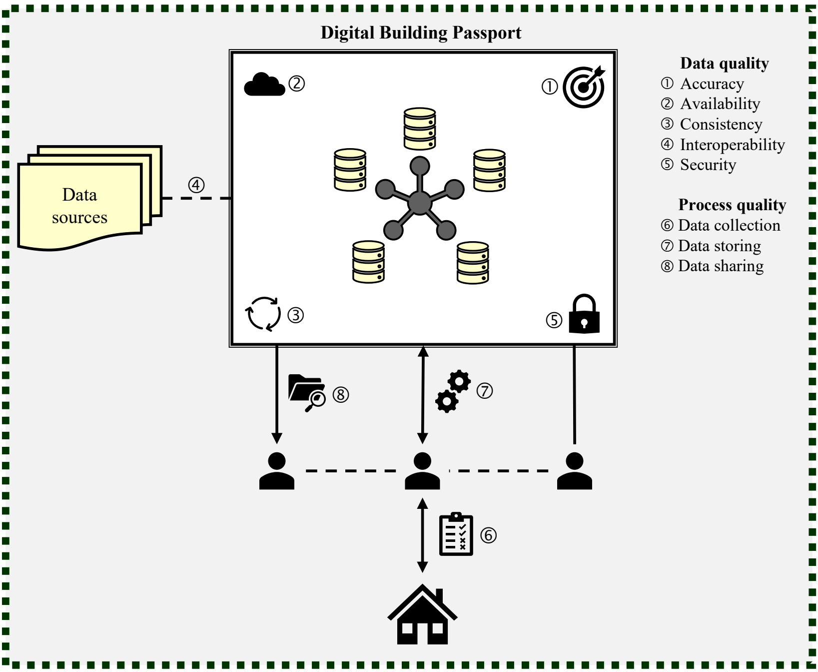


Figure 8.3: Overview on data and process qualities in a digital building passport

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).

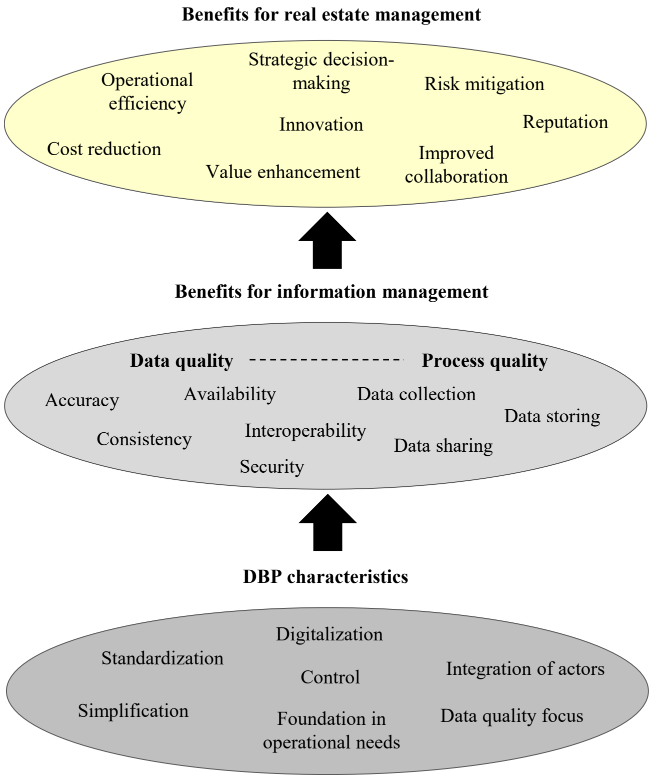


Figure 8.4: Chain of effects for benefits and potentials in digital building passports

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; High level of innovation; Flexibility to adapt business models to trends; Strong incentives for diffusion through financial gains; Focus on customer needs through value propositions	Profit-driven decisions may overlook social and environmental goals; Limited incentives for standardization, risking lock-in effects; High costs for early adopters
Non-profit-oriented private sector initiatives	Long-term sustainability-oriented goals; Generally more affordable for users due to non-profit nature	Limited resources compared to profit-driven businesses; Risk of less efficient solutions with reduced functionality and customer focus

Private developments for in-house use	Enables highly customized solutions; Often builds on existing real estate information management systems	Limited interoperability; Solutions tailored to specific companies' needs
Public sector initiatives	Focus on societal and environmental well-being; Opportunity for international alignment (e.g., EU initiatives); Access to diverse resources; Multiple roles in real estate incentivize holistic perspectives	Potential welfare loss due to market interventions; Short-term focus driven by election cycles; 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 2.3.4), 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.

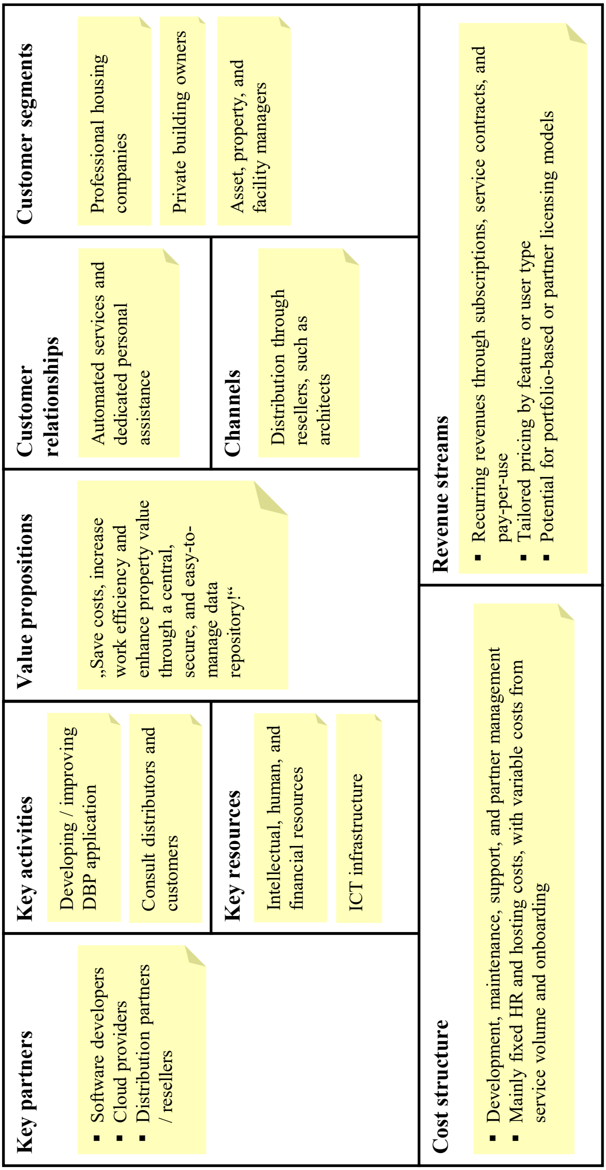


Figure 8.5: Example for a business model canvas for digital building passports

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.

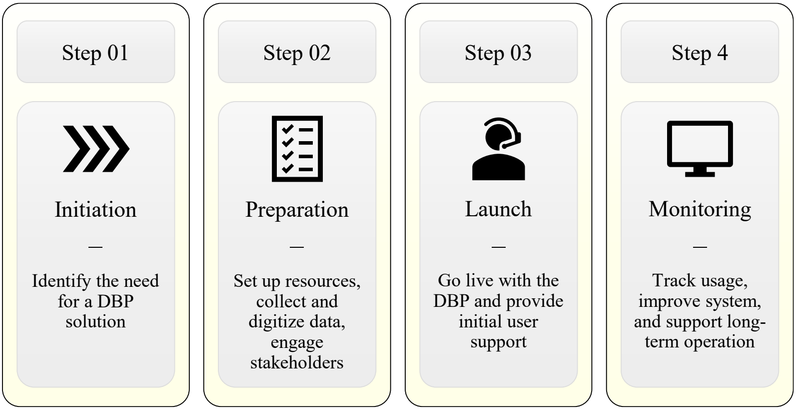


Figure 8.6: Universal implementation process for digital building passports

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.

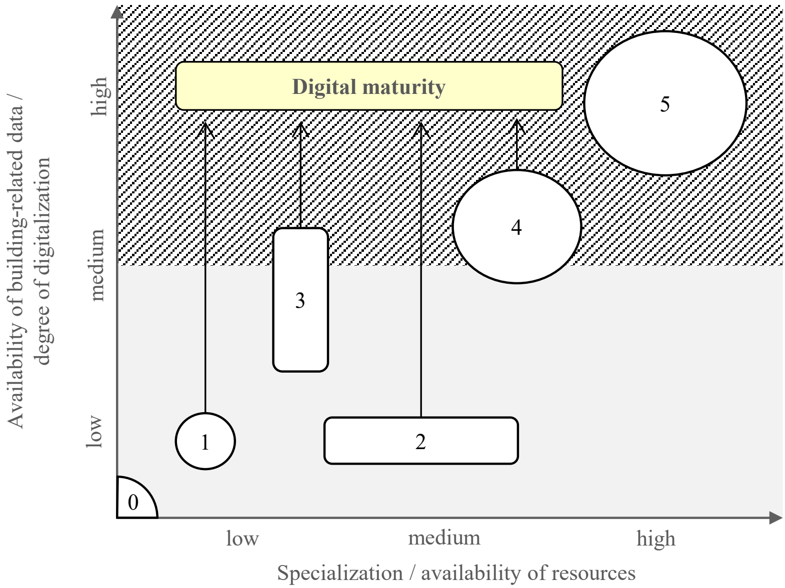


Figure 8.7: Transformation pathways for different actors to reach digital maturity

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 life cycle 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).

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

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.*

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

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

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

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

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_building-passport.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

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. (2022). 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. (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 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 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

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

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., 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

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.

Cyganiak, R., Wood, D., & Lanthaler, M. (2014, February 25). *RDF 1.1 Concepts and Abstract Syntax*. https://www.w3.org/TR/rdf11-concepts/

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

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 e-Book 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 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 Fachbericht 151:2007-01. *Technical product documentation – Facility management documentation – Building documentation*.

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

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., 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

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. (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

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

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)*.

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. (2025). *Individueller Sanierungsfahrplan*. https://www.gebaeudeforum.de/realisieren/isfp/

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.

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

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

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

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

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 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.

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

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).

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

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

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., & Mauricio, C. (2024). *Unlocking the potential of digital building logbooks for a climate-neutral building stock*. https://demoblog.eu/wp-content/uploads/2024/09/DemoBLog-policy-factsheet-WEBSept-2024-1.pdf

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.

Krogstie, J. (2012). *Model-Based Development and Evolution of Information Systems: A Quality Approach*. Springer London Limited.

Kumar, V., & 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., 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).

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.

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

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

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

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_Sustainability-Metrics_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

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

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

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

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

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

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

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

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

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

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

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

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

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/

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

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.

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. (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

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

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.

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., 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

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.

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

Susnjara, S., & Smalley, I. (2026, January 15). Distributed Hybrid Infrastructure. https://www.ibm.com/think/topics/distributed-hybrid-infrastructure

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

Tchouanguem Djuedja, J. F., Abanda, F. H., Kamsu-Foguem, B., Pauwels, P., Magniont, C., & Karray, M. H. (2021). An integrated Linked Building Data system: AEC industry case. *Advances in Engineering Software*, *152*, 102930. https://doi.org/10.1016/j.advengsoft.2020.102930

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

Toth, Z., 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

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

Volt, J., Toth, Z., 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

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

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, & 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 Integration of life cycle perspectives

Table A.1: Comparison of life cycle definitions from a building and task-oriented perspective based on (Alda & Hirschner, 2016; AHO, 2020; DIN EN 15978:2024-05)

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

Waste processing (C3) Disposal (C4)	New project development

A.2 Information modeling

A.2.1 Information system modeling

Table A.2: 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 sub-systems.
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 perspec-tives

A.2.2 Business modeling

Table A.3: 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 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.3 Actor roles in building-related tasks

Table B.3: 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	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	

Main perspective	Actor roles involved	Development and construction	Use and operation	End-of-life	Valuation	Risk management	Marketing	Public sector tasks	Sustainability assessment and	Non-financial reporting
	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)							
	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.4 Evidence of building-related data needs

This section provides an overview of the sources analyzed to derive building-related data needs across the task areas examined in section 3.3. The sources include normative documents, standards, guidelines, and selected industry publications. They are grouped according to the task areas they primarily inform. Detailed data-point mappings were used during the analysis but are not reproduced here for reasons of conciseness.

Table B.4: Sources used in the analysis of building-related data needs

Task area	Sources included
Development and construction	HOAI, 2013, building permit, VDI 6026:2015-04 part 1.1, DIN Fachbericht 151:2007-01, VDI 6070 Part 1, VDI 6039:2011-06
Use and operation	DIN 32835-2:2007-01, VDI-MT 3810 Part 1:2023-03, VDI 6041:2017-07, DIN SPEC 91462:2022-02, RICS (2020), RICS (2022a)
End-of-life stage	BMI and BMVg (2018), VDI 6210:2024-10 part 1, Osberghaus (2008)
Property valuation	Meins et al. (2011), Schlachter (2019), IAAO (2018)
Risk management	VÖB-Kommission für Bewertungsfragen (2006), Urschel (2010), NV-Versicherungen, Kiedrowski
Marketing	Helfrich (2021), real estate listings and brochures (https://www.immobilienscout24.de/, https://www.engelvoelkers.com/de/en, https://immo-center-karlsruhe.de/immobilienangebote/, https://www.immowelt.de/)
Public sector	Krause et al. (2022), Zensusdatenbank (2024), Danish Building and Dwelling Register (*The Central Register of Buildings and Dwellings (BBR)*, 2025; *Datamodel*, 2025; *Grunddataordbog*, 2024), Swiss Property Register (Bundesamt für Statistik [BFS], 2022)
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)
Corporate sustainability reporting	Climate Delegated Act, 2021, SFDR, 2019, CSRD directive, 2022

B.5 Taxonomy of building-related data points

B.5.1 Master data

Table B.5: 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
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.

Nr.	Data category and data points	Description
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

Nr.	Data category and data points	Description
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
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

Nr.	Data category and data points	Description
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
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,

Nr.	Data category and data points	Description
		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

Nr.	Data category and data points	Description
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
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.5.2 Inventory data

Table B.6: 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, 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

Nr.	Data category and data points	Description
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

Nr.	Data category and data points	Description
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 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

Nr.	Data category and data points	Description
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,

Nr.	Data category and data points	Description
		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 u-sage	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 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

Nr.	Data category and data points	Description
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.5.3 Economic and legal data

Table B.7: 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

Nr.	Data category and data points	Description
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
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

Nr.	Data category and data points	Description
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
360	**Contracts**	Legally binding agreements related to the construction, operation, management, and financial aspects of the building

Nr.	Data category and data points	Description
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

Nr.	Data category and data points	Description
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.5.4 Performance data

Table B.8: 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

Nr.	Data category and data points	Description
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
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

Nr.	Data category and data points	Description
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

Nr.	Data category and data points	Description
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
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.6 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.9: 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 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.1: 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.2: 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.2 Data analytics throughout the life cycle

Table C.3: 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	Bilal et al. (2016, p. 508), Rampini and Cecconi (2022, p. 899)

		protection and structural safety.	
	Predictive analytics for material selection	Evaluates materials based on performance and sustainability criteria using ML algorithms.	Baduge et al. (2022, p. 10)

Table C.4: 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)

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		

		Sensitive / confidential	Long validitiy period	Legal retention requirement	High structurization
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 Official German building passport proposal 2001

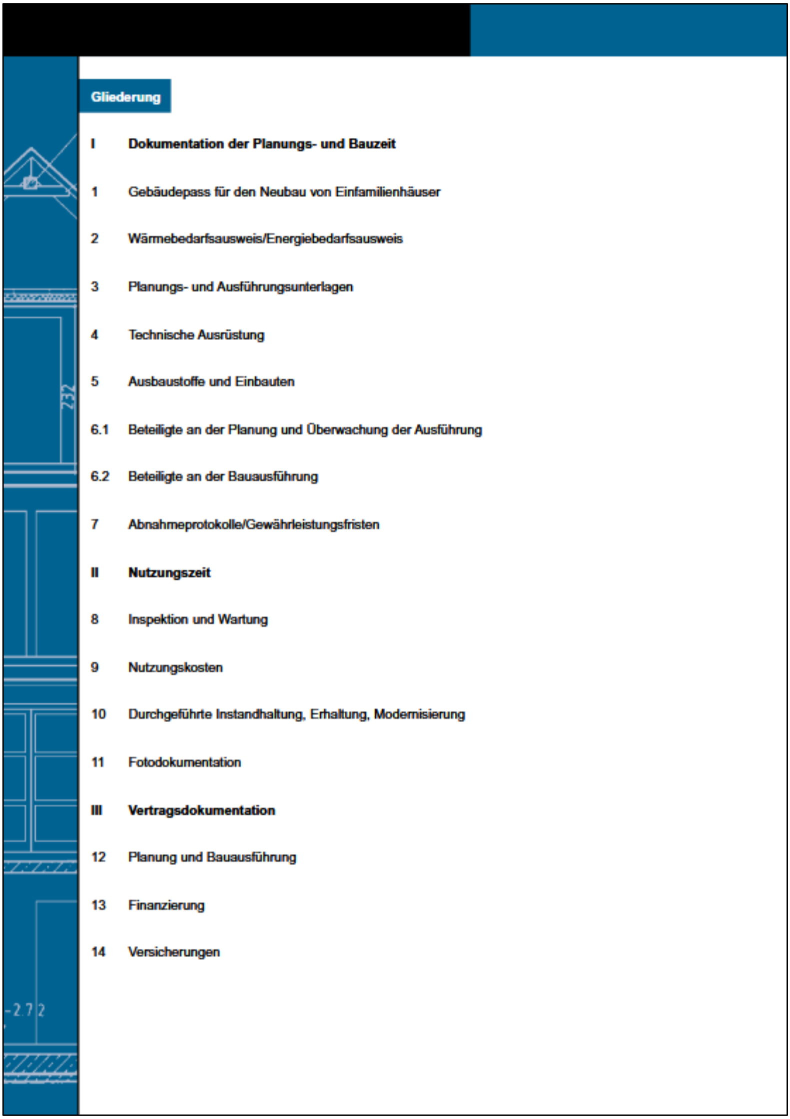
The following table shows the content that was proposed by the German Ministry of Transport, Building and Housing (2001) for building passports. In addition to the information that was to be filled in in the form, the explicit extension with appendices, for example in the form of design documents, was 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.1.2 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.1.3 Material data sheet proposal for building passports

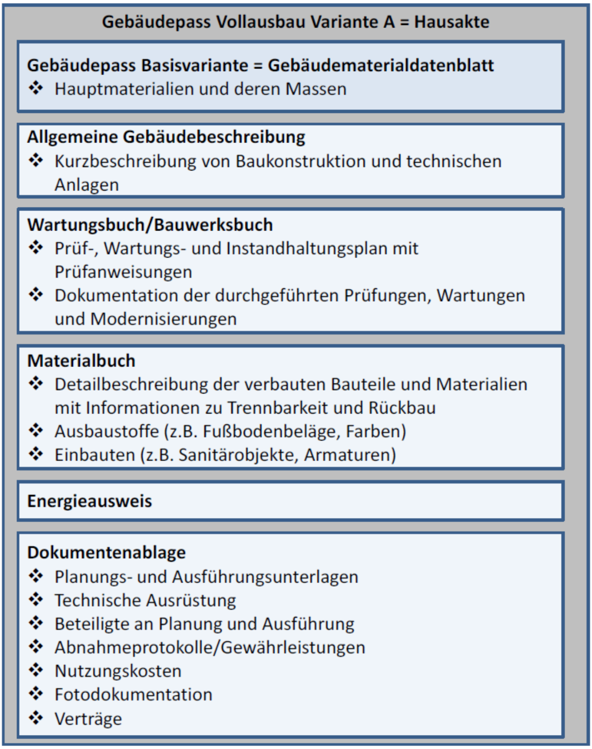


Figure E.2: Material data sheets as an integral part of building passports (Reisinger et al., 2014, p. 88)

E.1.4 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.1.5 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 Inter-ventie Dossier	Belgium	Opera-tional	Mandatory	Healthy and safety of build-ing users	(Vlaanderen, 2023)
E-con-struction platform	Estonia	Tested	Voluntary	Improve public real estate ser-vices and infor-mation man-agement including 3D view	(e-ehitus, 2025)
Woningpas	Belgium	Opera-tional	Voluntary	Improve energy efficiency of the building stock through better data availability	(EC, 2019; Hy-potheek.winkel, 2023; Liferay DXP, 2023)
Bedrebolig	Denmark	Opera-tional	Voluntary	Support build-ing owners in planning en-ergy renova-tions	(Energistyrelsen, 2014)
Le carnet numérique du logement	France	Opera-tional	Partly mandatory	Support build-ing owners in their infor-mation man-agement	(Carnet-nu-merique.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.1.6 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.1.7 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

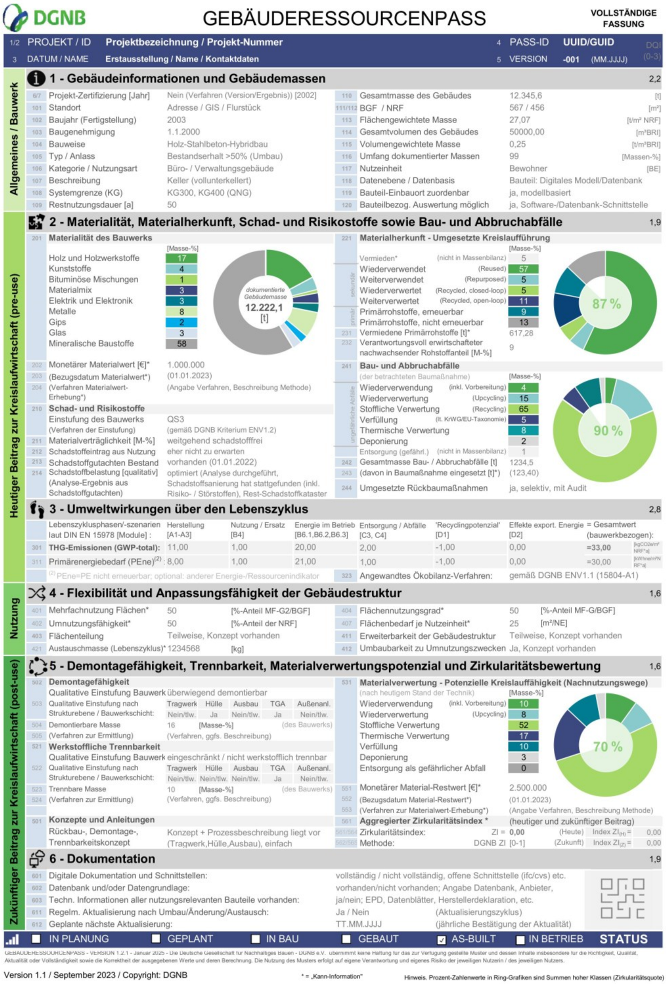


Figure E.3: Example for a building resource passport for existing buildings (DGNB, 2023a)

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.

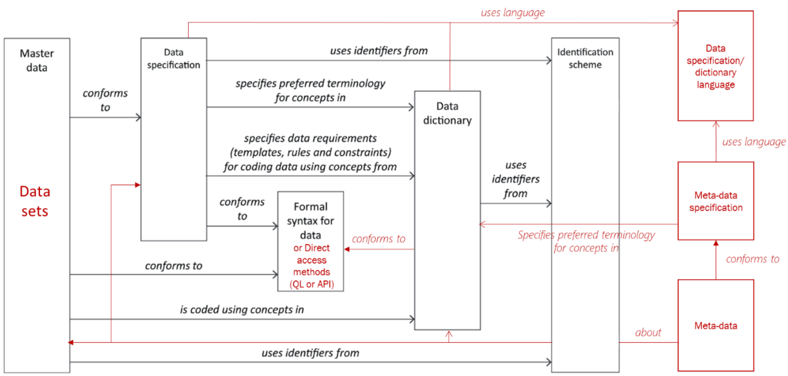


Figure F.1: Data architecture for a semantic data model in digital building passports (Böhms et al., 2023, p. 9)

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 Detailed concept for definition of entities and relationships	Only incorporates structured data in JSON format 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 Takes into account other construction works than buildings Detailed concept for definition of entities and relationships 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 Large library of entities and use cases	Focused more on processes than on building-related data Lack of abstraction mechanisms
RESO data dictionary (RESO, 2023)	Attempt for standardization of building-related terms and concepts Large library of entities	Focused more on processes than on building-related data 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 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 Availablability in various data formats and schemas creates interoperability	Focus on structural and construction stage aspects Complexity of the schema Lack of flexibility in individual processes Lack of semantic completness
EC DBL semantic data model (Böhms et al., 2023)	Orientated on the needs of DBPs/DBLs on EU level Ontology-based features, such as knowledge graph presentation and high-level of interoperability Combination of ontology and dictionary 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 Limited specification of semantics (relationships between entities)

F.3 Data ontology approach for linked data

Böhms et al. (2023) developed a semantic data model embedded in a data architecture for DBLs in the EU. It shows the capabilities of linked data / semantic web implementations based on RDF.

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 Shapes Constraint Language (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).

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 aiming to keep 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.4 Factors on attribute-based access control

Table F.2: 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,	Resource availability/quality (data, ICT)	

service-level agreements)	
Experience level in DBP use (action history)	Output quality (data, requirements for further action)

F.5 Job-sharing between building information systems

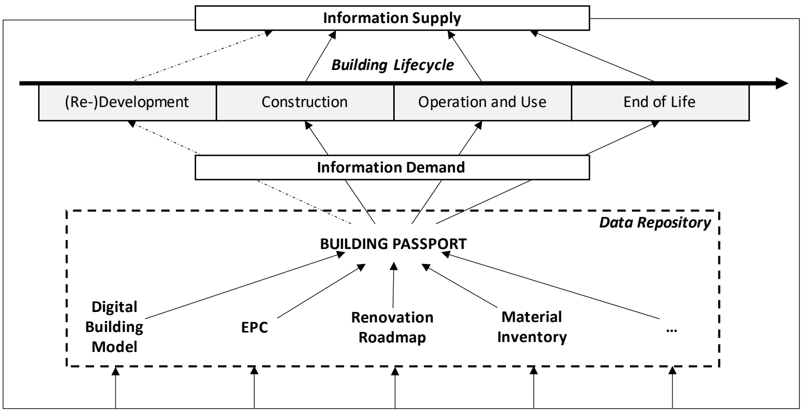


Figure F.2: Conceptual proposal for an integration of selected tools into a digital building passport (Buchholz & Lützkendorf, 2022, p. 7)

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.

KARLSRUHER SCHRIFTEN ZUR BAU-, WOHNUNGS- UND IMMOBILIENWIRTSCHAFT

ISSN 1863-8694

Band 1 David Philipp Lorenz
The Application of Sustainable Development Principles to the Theory and Practice of Property Valuation.
ISBN 978-3-86644-089-0

Band 2 Monika Bachofner
Analyse von Systemen der Wohneigentumsfinanzierung in Europa und die Beurteilung ihrer Effizienz.
ISBN 978-3-86644-255-9

Band 3 Christian Jaeger
IFRS-Controlling von Wohnungsunternehmen. Ein Beitrag zum wertorientierten Bestandsmanagement in der Wohnungswirtschaft.
ISBN 978-3-86644-443-0

Band 4 Oliver Urschel
Risikomanagement in der Immobilienwirtschaft. Ein Beitrag zur Verbesserung der Risikoanalyse und -bewertung.
ISBN 978-3-86644-492-8

Band 5 Martin Wilhelm
Instandhaltungsstrategien unter Berücksichtigung stochastischer Alterungsprozesse. Ein Beitrag zur systematischen Bewirtschaftung von Immobilien.
ISBN 978-3-86644-638-0

Band 6 Christoph Rohde
Integration von Nachhaltigkeitsaspekten in Prozesse des immobilienwirtschaftlichen Risikomanagements.
ISBN 978-3-86644-733-2

Band 7 Sebastian Drewer
Entwicklung von Hilfsmitteln für die Planung und den Variantenvergleich von Beförderungssystemen in Gebäuden am Beispiel von Aufzügen.
ISBN 978-3-7315-0490-0

Die Bände sind unter www.ksp.kit.edu als PDF frei verfügbar oder als Druckausgabe bestellbar.

Band 8 Benjamin Ströbele
Bereitstellung von Umweltdaten im Baubereich auf der Grundlage statistischer Zusammenhänge zwischen den Wirkungsindikatoren einer Ökobilanz.
ISBN 978-3-7315-0708-6

Band 9 Peter Michl
Hedonische Preisindizes für Transaktionen von Wohneigentum – dargestellt am Beispiel der Stadt Karlsruhe. Ein Beitrag zur Bereitstellung von Zeitreihen für die Marktwertermittlung und Marktprognose.
ISBN 978-3-7315-0797-0

Band 10 Anjulie Jäger
Der Einfluss nachhaltigkeitsbezogener Objektmerkmale auf den Wert von Immobilien – ein Beitrag zur Weiterentwicklung von Datenhaltung und Wertermittlungsverfahren.
ISBN 978-3-7315-1094-9

Band 11 Thomas Friedrich
Integration von Nachhaltigkeitsaspekten in die operativen und strategischen Prozesse von Kapitalverwaltungsgesellschaften für Immobilienfonds.
ISBN 978-3-7315-1189-2

Band 12 Matthias Buchholz
Information Management in the Building Life Cycle – The Emerging Role of Digital Building Passports.
ISBN 978-3-7315-1478-7

Karlsruher Institut für Technologie
Lehrstuhl Ökonomie und Ökologie des Wohnungsbaus

This work addresses the long-standing challenge of managing building-related data across the entire life cycle, an issue that has remained unresolved despite decades of effort. In the context of advancing digitalization and increasing sustainability requirements, it examines the requirements for life cycle building information systems that enable informed decision-making and transparency. Based on a systematic analysis, digital building passports are identified as the most promising approach, offering a comprehensive and integrative solution beyond existing fragmented concepts. This work develops a coherent system architecture and provides a structured foundation for their implementation and standardization, contributing to both academic research and emerging practice in the real estate industry.

ISBN 978-3-7315-1478-7

9 783731 514787

ISSN 1863-8694
ISBN 978-3-7315-1478-7

Gedruckt auf FSC-zertifiziertem Papier