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Christoph R. W. Kempf

University Research Results in Corporate Product Engineering - A Core Aspect of Reference System Management in System Generation Engineering

Ergebnisse universitärer Forschung in der Produktentstehung von Unternehmen - Ein Kernbestandteil des Referenzsystemmanagements in der Systemgenerationsentwicklung

Band 186

Systeme ▪ Methoden ▪ Prozesse

Univ.-Prof. Dr.-Ing. Dr. h.c. A. Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen
(Hrsg.)

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University Research Results in Corporate Product Engineering - A Core Aspect of Reference System Management in System Generation Engineering

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Vorwort der Herausgeber

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den Forschungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient seit mehr als 20 Jahren als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK - Institut für Produktentwicklung Karlsruhe* am Karlsruher Institut für Technologie (KIT) verfügbar. Die Forschung des IPEK ist dabei strukturiert in die Kategorien Systeme, Methoden und Prozesse, um so der Komplexität heutiger Produktentwicklung ganzheitlich gerecht zu werden. Erst die Verknüpfung dieser drei Kategorien ermöglicht die Synthese innovativer Systeme durch Nutzung neuester Methoden und Prozesse. Gleichzeitig werden durch die Systemsynthese die erforschten neuen Methoden und Prozesse validiert und deren Mehrwert für die Praxis abgesichert. Dieses Forschungskonzept prägt nicht nur das IPEK-Leitbild, sondern auch den Charakter dieser Schriftenreihe, da immer alle drei Kategorien und deren Wechselwirkungen berücksichtigt werden. Jeder Band setzt hier individuelle Schwerpunkte und adressiert dabei folgende Forschungsgebiete des IPEK:

- das Entwicklungs- und Innovationsmanagement,
- die Entwicklungs- und Konstruktionsmethodik,
- der Leichtbau von der Ebene des ganzen Systems bis hinunter zur Optimierung des Bauteils,
- die Validierung technischer Systeme auch unter Berücksichtigung der NVH Aspekte (Noise, Vibration, Harshness) mit dem Fokus auf Schwingungen und Akustik an Komponenten und in den Gesamtsystemen sowie deren subjektiver Beurteilung durch den Menschen,
- die Antriebssystemtechnik mit den Schwerpunkten komplette Antriebslösungen für Fahrzeuge und Maschinen,
- das Design, die Tribologie und Erprobung von Kupplungen und Bremsen sowie
- die Gerätetechnik mit dem Schwerpunkt auf Power-Tools.

Die Forschungsberichte stellen Ergebnisse unserer Forschung sowohl anderen Wissenschaftlern als auch den Unternehmen zu Verfügung, um damit die Produktentwicklung in allen ihren Facetten mit innovativen Impulsen zu optimieren.

Albert Albers und Sven Matthiesen

* Eh.: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe (TH)

Vorwort zu Band 186

Joseph A. SCHUMPETER stellte bereits in seiner Theorie der Innovation, die er insbesondere in „Theorie der wirtschaftlichen Entwicklung“ von 1911 sowie später in „Capitalism, Socialism and Democracy“ von 1942 darlegte, im Kern fest: „Jede Innovation entsteht durch Neukombination bestehender Ressourcen und Technologien“. Er beschreibt dabei fünf Typen solcher Innovationen:

- die Einführung eines neuen Gutes, die Schaffung eines Produkts, das den Konsumenten bisher so unbekannt war,
- die Einführung einer neuen Produktionsmethode, eine Methode, die in der betreffenden Branche noch nicht erprobt wurde – unabhängig davon, ob sie auf einer wissenschaftlichen Entdeckung beruht oder eine neue Art des kommerziellen Umgangs mit einer Ware darstellt,
- die Erschließung eines neuen Absatzmarktes – ein Markt, in dem die betreffende Branche des Landes bisher noch nicht vertreten war, unabhängig davon, ob dieser Markt vorher existierte oder nicht,
- die Eroberung einer neuen Bezugsquelle von Rohstoffen oder Halbfabrikaten – unabhängig davon, ob diese Bezugsquelle bereits existiert, oder neu geschaffen wurde,
- die Durchführung einer Neuorganisation, beispielsweise die Schaffung einer Monopolstellung oder der Durchbruch einer bisherigen Monopolstellung.

SCHUMPETER betont in seinen Werken, dass diese Innovationen durch die Neukombination bereits vorhandener Elemente entstehen und somit das wirtschaftliche Wachstum vorantreiben. Dieses Konzept der neuen Kombinationen bildet den Kern seiner Theorie der wirtschaftlichen Entwicklung und wurde von ALBERS und seiner Gruppe – beginnend im Jahre 2010 – in ein grundlegendes Konzept der Entwicklung technischer Systeme aufgenommen und überführt. Das Modell des *System Generations Engineering (SGE)* nach ALBERS beschreibt diesen Prozess als systematische Entwicklung von neuen Systemgenerationen durch Übernahme-, Ausprägungs- und Prinzipvariation (*carry over-, attribute- und principle-variation*). Kern dieses Ansatzes ist dabei die Abbildung eines Referenzsystems – das aus einer Vielzahl von Elementen besteht, die zuvor komponiert werden müssen – durch die oben angesprochenen Variationsoperatoren auf die neue Systemgeneration. Dabei sind die Elemente des Referenzsystems sowohl aus internen Quellen des Unternehmens, zum Beispiel anderen Produktgenerationen oder Produktlinien, zu identifizieren, oder sie stammen aus externen Quellen. Diese externen Quellen können aus einer Wettbewerbsanalyse im Umfeld des eigenen Unternehmens, oder aber auch durch branchenübergreifende Analysen, sowie durch eine systematische Analyse des Standes der Forschung gewonnen werden. Durch ein strukturiertes Referenzsystemmanagement kann die Innovationskraft von Unternehmen erheblich gesteigert und auch der Transfer von Forschungsergebnissen in die industrielle Produktentwicklung gezielt optimiert werden. Dabei stellen sich allerding gerade bei der Nutzung von Forschungsergebnissen, die auch bereits SCHUMPETER in seinen frühen Werken angeregt und angesprochen hat, als Referenzsystemelemente große Herausforderungen, da die Forschungsergebnisse im Allgemeinen sowohl im Bereich der Aufbereitung, des Reifegrades und der Dokumentation deutlich weniger konkretisiert sind, wie zum Beispiel die Teilsysteme, oder auch Konzepte und Ansätze aus der eigenen Branche oder gar aus dem eigenen Unternehmen. Auf der anderen Seite können gerade die Ergebnisse der Forschung wichtige Impulse geben, um ein hohes Innovationspotenzial und einen hohen Neuheitsgrad in der Systemgenerationsentwicklung zu kreieren. Insbesondere bei der im Modell der *SGE* sogenannten *G_1 Entwicklung*, also Systemgenerationen, die erstmalig in dieser Art ohne einen direkten Architekturvorgänger entwickelt werden müssen, kann dieser Ansatz wertvoll sein. Aber auch bei der Neuentwicklung von laufenden Systemgenerationen ist die Integration von Ergebnissen der aktuellen Forschung, zum Beispiel im Bereich der Teilsysteme oder Funktionsträger, eine Möglichkeit, das Innovationspotenzial zu erhöhen. Wichtig ist aber auch zu verstehen, dass die Ergebnisse der Forschung niemals so weit ausgereift sein können, dass sie komplette neue Systemgenerationen in ihrer Architektur mitbringen. Hier ist dann die kreative Kombination der entsprechenden Referenzsystemelemente zu der neuen Systemgeneration notwendig. Die Frage, was ist zu tun, um die Ergebnisse der Forschung strukturiert zu analysieren und aufzubereiten, um sie dann in die Innovationsprozesse der Unternehmen erfolgreich einbinden zu können, ist eine spannende wissenschaftliche Fragestellung, der sich Herr Dr.-Ing. Christoph Kempf in seiner Arbeit gestellt hat. Die Ergebnisse leisten dabei sowohl einen wichtigen Beitrag zur Grundlagenforschung im Bereich der Produktentstehung als auch mit konkreten Hinweisen und Vorschlägen Impulse für Forschende, Forschungsförderer aber auch Unternehmen um die Ergebnisse der Forschung schneller in die Nutzung zu bringen.

März, 2025 Albert Albers

Kurzfassung

Das Modell des SGE – System Generation Engineering nach Albers beschreibt die Entwicklung neuer Produkte als die Entwicklung neuer Systemgenerationen auf der Basis bereits bestehender Referenzen. Diese Referenzen werden als Referenzsystemelemente innerhalb des Referenzsystems modelliert. Das Referenzsystem selbst ist ein Kernelement, um das Potenzial der Systemgenerationsentwicklung zu heben und neue Systeme mit hohem Innovationspotenzial effizient zu entwickeln. Hier kann Forschung als wertvolle Quelle für Referenzen dienen. Diese Arbeit zielt darauf ab, Referenzsystemmanagement in der Systemgenerationsentwicklung einzuführen und Forschung als Quelle für potenzielle Referenzsystemelemente zu erschließen. Daher besteht das Ziel darin, die Nutzbarkeit von Forschungsergebnissen als Referenzsystemelemente in der Produktentwicklung von Unternehmen zu verbessern.

Um dieses Zieles zu erreichen, analysiert die vorliegende Arbeit zunächst den Stand der Forschung, um die Rolle von Referenzen in der Produktentwicklung sowie den Wissens- und Technologietransfer aufzuarbeiten. Anschließend werden die Grundlagen des Referenzsystems erforscht und konsolidiert. Dabei werden die Einflussfaktoren aus der Entwicklungssituation und dem Entwicklungskontext untersucht, die sich auf das Referenzsystem auswirken. Es werden außerdem die verschiedene Quellen für Referenzen ermittelt und Methoden und Ansätze zur Suche und Sammlung von Referenzen aus diesen Quellen identifiziert. Darüber hinaus wird die innere Struktur des Referenzsystems als Grundlage für die Entwicklung modellbasierter Ansätze, die auf dem Referenzsystem basieren, definiert.

Des Weiteren wird in dieser Arbeit die aktuelle Rolle und Verwendung von Referenzen aus der Forschung in der Produktentwicklung in Unternehmen eingehend untersucht. Es wird ein Klassifizierungsmodell entwickelt, mit dem verschiedene Arten von Forschungsergebnissen anhand ihres Reifegrads kategorisiert werden können. Basierend auf dem so gewonnenen Verständnis werden die Gründe der Produktentwickelnden Referenzen aus der Forschung zu verwenden, die Auslöser, die die Suche nach diesen Referenzen initiieren und die Methoden und Ansätze, die sie bei der Suche nach Referenzen aus der Forschung und deren Übertrag in ihr Referenzsystem anwenden, untersucht. Außerdem werden die Herausforderungen, mit denen Produktentwickelnde bei der Suche nach oder der Anwendung von Referenzen aus der Forschung konfrontiert sind, identifiziert und diskutiert.

Schließlich werden alle Erkenntnisse und Ergebnisse dieser Arbeit in einer Reihe von konsolidierten Empfehlungen für Produktentwickelnde und Unternehmen, Forschende

und Forschungseinrichtungen sowie Fördergeber und (Forschungs-)Politik vorgestellt. Diese Empfehlungen zielen darauf ab, die Nutzbarkeit von Forschungsergebnissen als Referenzsystemelemente in der Produktentwicklung in Unternehmen zu verbessern.

Abstract

The model of SGE – System Generation Engineering by Albers describes the development of new products in product engineering as the development of new system generations based on already existing references. These references are modeled as reference system elements within the reference system. The reference system itself is a core element to leverage the potential of system generation engineering to develop new systems with high innovation potential efficiently. Here, research can serve as a potent source for references as inputs. This thesis aims to introduce reference system management to system generation engineering and develop research as a source for potential reference system elements. Therefore, the objective is to improve the usability of research results as reference system elements in corporate product engineering.

To achieve this objective, this thesis first analyzes the state of research to understand the role of references in product engineering as well as knowledge and technology transfer. Subsequently, the thesis develops the fundamentals of the reference system. It investigates the influencing factors from the engineering situation and context that impact the reference system. Further, it examines the different sources for references and identifies methods and approaches to search for and collect references from these sources. Additionally, it defines the internal structure of the reference system as a basis for developing model-based approaches that rely on the reference system.

Furthermore, this thesis conducts an in-depth investigation of the current role and usage of references from research in corporate product engineering. It develops a classification model to categorize different types of research results based on their maturity level. Based on the gained understanding, this thesis examines the reasons why product engineers use references from research, the triggers that initiate their search for these references, and the methods and approaches they employ to search for and apply references from research in their reference system. It also identifies and discusses the challenges product engineers face when searching for or applying references from research.

Finally, this thesis condenses all insights and findings into a set of recommendations for corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers. These recommendations aim to improve the usability of research results as reference system elements in corporate product engineering.

Acknowledgment

This thesis was written as part of my work as a doctoral researcher at IPEK – Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT). I would like to take this opportunity to sincerely thank everyone who has accompanied and supported me along the way.

First and foremost, I would like to express my gratitude to my doctoral advisor, Univ.-Prof. Dr.-Ing. Dr. h. c. Albert Albers, for his invaluable support, guidance, and trust throughout my research. He has played a crucial role in shaping my work. I am particularly grateful for the opportunities he provided me to take on responsibilities and challenges that pushed me beyond my initial expectations, allowing me to grow scientifically, professionally, and personally.

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Many thanks, I want to express to my mentors and friends that I found on the way. Thank you, Dr.Ing. Katharina Ritzer, Dr.Ing. Jonas Heimicke, and Dr.-Ing. Simon Rapp. Our discussions were always delightful, gave me many ideas, and, most importantly, confidence in my research.

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Finally, my deepest appreciation goes to my family and friends, who have shaped me into the person I am today. They always gave me confidence in myself and helped me clear my mind outside the scientific and professional world.

Karlsruhe, April 3, 2025

„Es ist nicht genug zu wissen, man muß auch anwenden; es ist nicht genug zu wollen, man muß auch tun.“ – Knowing is not enough; we must apply. Willing is not enough; we must do.

– Johann Wolfgang von Goethe

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Acronyms

AE	Advanced Engineering
AI	Artificial intelligence
AS	Advanced Systems
ASD	Agile Systems Design
ASE	Advanced Systems Engineering
AV	Attribute variation
BMBF	German Federal Ministry of Education and Research
CoDiCoFRP	Continuous discontinuous fiber reinforced polymers
CRC	Collaborative Research Center
CV	Carryover variation
DFG	German Research Foundation
DRL	Design readiness level
DRM	Design research methodology
DS	Descriptive Study
E	Engineering generation
EUV	Extreme Ultraviolet radiation
G	System generation
GRK	Graduiertenkolleg (English: IRTG)
IPEK	Institute of Product Engineering
iPeM	Integrated Product engineering Model
IRL	Integrated readiness level
IRTG	International Research Traning Group
KaSPro	Karlsruhe School of Product Engineering
KIT	Karlsruhe Institute of Technology

MBSE	Model-based Systems Engineering
OEM	Original equipment manufacturer
PGE	Product Generation Engineering
PS	Prescriptive Study
PV	Principle variation
R	Reference system
RR	Research result
RRL	Research readiness level
RSE	Reference system element
SE	Systems Engineering
SGE	System Generation Engineering
TRL	Technology readiness level

1 Introduction

„Das Wissen ist das einzige Gut, das sich vermehrt, wenn man es teilt." – Knowledge is the only resource that increases when shared.

– Marie von Ebner-Eschenbach

1.1 Motivation

Product engineers develop new systems based on existing systems (Albers, 2010). The reuse and incorporation of existing systems help reduce development risks and costs (Deubzer & Lindemann, 2009). Thus, engineers can develop new systems in a shorter time (Eckert et al., 2004). The evolution of classical mechanical products via mechatronic solutions to Advanced Systems, intelligent cyber-physical systems, especially requires these efficient and effective development processes. Increasing complexity due to increasing levels of dynamic interconnections within the systems and to other systems, as well as sociotechnical integration, challenge product engineering. (Dumitrescu et al., 2021) Here, research offers valuable input. Apple's iPhone, Boston Dynamic's robot Spot, and Trumpf's and Zeiss' EUV[1] technology are three examples of very successful advanced systems. All three examples have in common that the engineers used input from research in their engineering activities to add new functionality or improve their systems. Figure 1.1 shows exemplary references from research that contributed to the development of these systems. As the examples show, research can support the development of successful new system generations – innovations – coping with the challenges.

[1] Extreme ultraviolet radiation

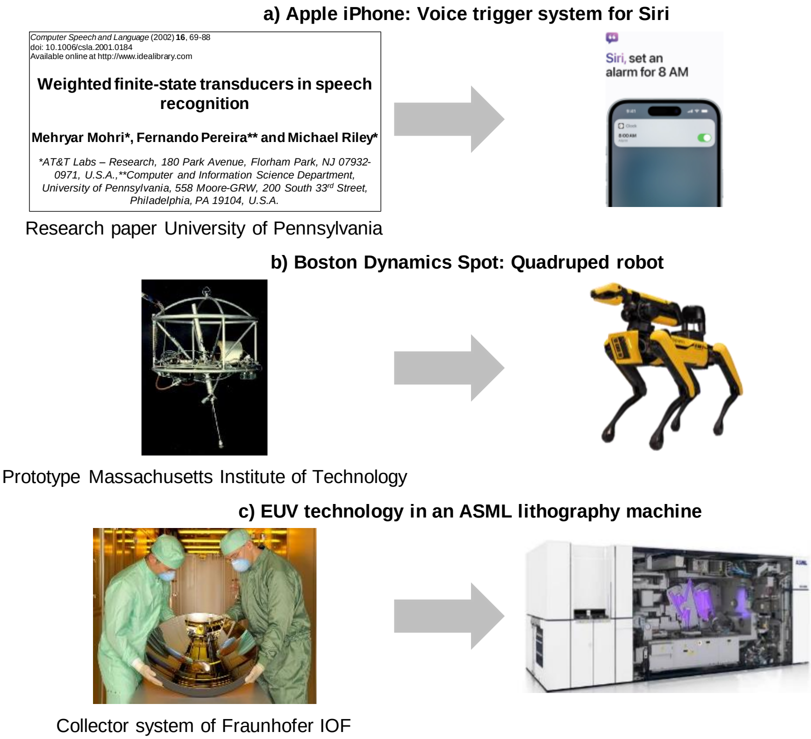


Figure 1.1: Three examples of successful Advanced Systems that used research results as references: a) Voice trigger system for Siri of Apple's iPhone (Apple Machine Learning Research, 2023) (images: (Mohri et al., 2002) and (Apple, 2024)), b) Boston Dynamic's robot Spot (Raibert et al., 2008; Williams, 2015) (images: (MIT Leg Laboratory, 1983) and (Boston Dynamics, 2024)), and Trumpf's and Zeiss' EUV technology (Fraunhofer-Gesellschaft, 2020) (images: (Fraunhofer IOF, 2011) and (Trumpf, 2024)) were all developed using research results as references.

Research and the commercialization of its results are vital to facing the major societal challenges (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007). The recent COVID-19 pandemic illustrated the power and necessity of research and the technical commercialization of research results for societies to cope with even the largest global societal challenges. The vaccines developed were based on the mRNA technology discovered and developed in research projects (Dolgin, 2021; Jain et al., 2021). Due to the demographic shift, many more health- and age-related challenges will arise that also require technological answers.

Another current major challenge is the complex of energy consumption and climate change. Among other things, these challenges are core drivers for researching new lightweight material systems. When commercialized and integrated into new systems, lightweight material systems can help reduce energy consumption, which is one aspect of facing these challenges. Here, the International Research Training Group (IRTG) "Integrated engineering of continuous-discontinuous long fiber reinforced polymer [(CoDiCoFRP)] structures" (IRTG 2078[2]) of the German Research Foundation (DFG) works on developing new lightweight material systems in all different aspects of characterization, simulation, production/ technology, and design to contribute to facing these challenges (Böhlke et al., 2018). Besides the research itself, the transfer of the research results is a core component of the IRTG to contribute to overcoming the named challenges. Thus, being part of the IRTG, this thesis focuses on this transfer and investigates how the usability of research results in corporate product engineering can be improved.

1.2 Focus of This Thesis

This thesis contributes an additional component to the KaSPro – Karlsruhe School of Product Engineering. The KaSPro represents a comprehensive view and understanding of product engineering. Within the KaSPro, the model of SGE – System Generation Engineering by Albers (Albers, Bursac, & Wintergerst, 2015) serves as a foundational element as it describes the development of new products. The model of SGE describes the development of new products in product engineering as the development of new system generations based on already existing references via different types of variation. These references are modeled as reference system elements within the reference system[3].

The focus of this thesis is the investigation of research as a source of reference system elements for corporate product engineering. Thus, the aim is to support and improve knowledge and technology transfer from research to corporate product

[2] German: Graduiertenkolleg – GRK 2078
[3] Section 2.3.1 explains the model of SGE by Albers in detail.

engineering. Therefore, this thesis introduces reference system management as a core aspect of product engineering to support the development of successful new products or systems based on the model of SGE – System Generation Engineering by Albers. Reference system management organizes the synthesis of reference systems for the development of new systems in corporate engineering. Thus, this thesis will first research the fundamentals of reference system management to set the basis. Here, foci are factors that influence the creation of a suitable reference system for the development of a new system, methods and tools of reference system management that support searching and collecting reference system elements, and the internal structure of the reference system. These investigations form the basis to explore the field of research as a source for reference system elements in-depth. Thus, this thesis investigates the triggers for using research results as reference system elements, methods and approaches for collecting and using them, and challenges and barriers that exacerbate the search and usage. While collaborative projects of industry and research partners are an important measure for technology and knowledge transfer, this thesis does not specifically focus on improving such collaboration formats. However, it holistically considers the usage of research results as reference system elements. All findings result in recommendations that help improve the usability of research results as reference system elements. Additionally, with the theoretical considerations of reference system management, this thesis provides the foundations for the systematic description and support of the reference system's synthesis. Figure 1.2 illustrates the subject of this thesis, research areas that form the basis, research areas to which this thesis contributes, and further useful research areas.

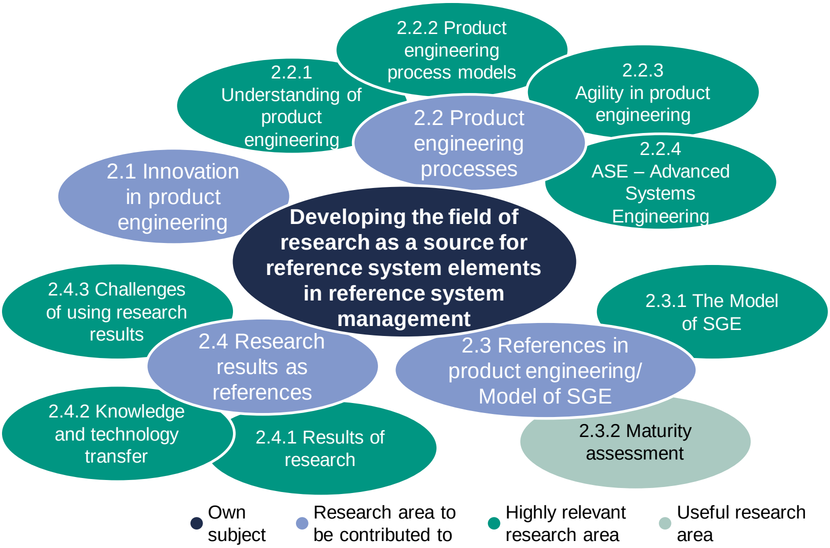


Figure 1.2: Focus of this thesis. The ARC-Diagram shows the subjects this thesis relies on and contributes to (ARC – Areas of relevance and contribution (Blessing & Chakrabarti, 2009)).

1.3 Structure of This Thesis

As shown in Figure 1.3, this thesis consists of 10 chapters.

Chapter 2 presents the state of research. This chapter first introduces the term innovation. Second, it presents product engineering, including different process models and Advanced Systems Engineering. Third, it describes the state of research on the role of references in product engineering and presents the model of SGE – System Generation Engineering. Finally, it presents research as a source for potential references.

Chapter 3 introduces the research need and this thesis' research objective. Subsequently, it presents the basic assumption on which this thesis is based and the research questions that provide the structure.

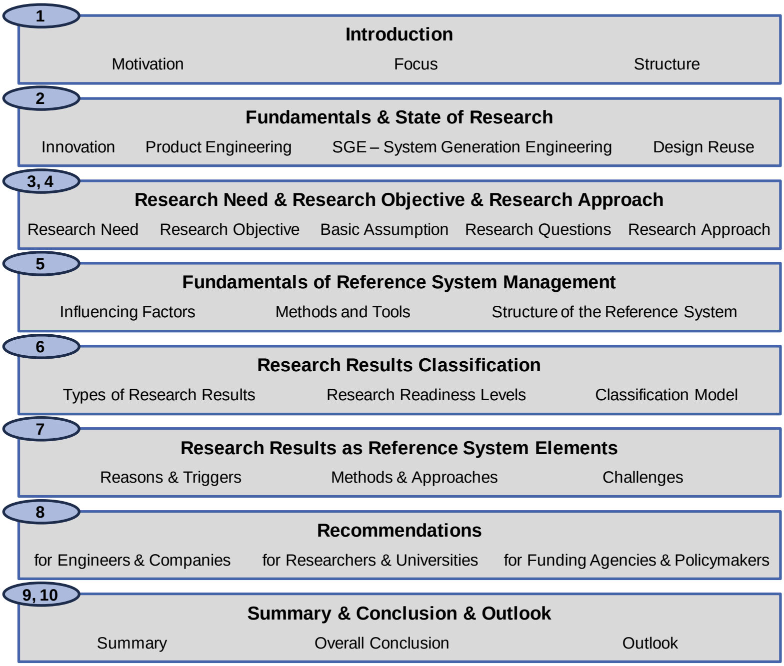


Figure 1.3: Structure of this thesis.

Chapter 4 sets this research project into a research framework for design research based on the Design Research Methodology (DRM) of Blessing and Chakrabarti (2009). It presents the research approach by explaining the stages and introducing the research environments and methods used.

Chapter 5 describes the fundamentals of reference system management. It first investigates factors influencing the reference system and its elements from the context of product engineering. These investigations converge in developing a descriptive model of influencing factors on the reference system. Second, this chapter collects and presents methods and tools described in the literature and used in practice to search for and collect reference system elements. Therefore, it also defines the different sources for reference system elements. These findings result in a model linking potential knowledge spaces as sources for reference system elements to the reference system via the identified methods and tools. Third, this chapter structures the reference system by defining three subsystems. This description prepares the reference system and, thus, the model of SGE for the application in Advanced Engineering approaches using, e.g., Model-based Systems Engineering. Chapter 5 sets the foundation for further in-depth research in reference system management.

Chapter 6 explores research as a source for corporate reference system elements. It sets the foundation by investigating different types of research results and developing a classification model for them. Furthermore, it defines a scale to assess the maturity of research results.

Chapter 7 investigates the current use of research results as reference system elements in corporate product engineering. Therefore, it first analyzes different triggers and the reasons for using research results as reference system elements. Second, it describes corporate engineers' methods and approaches to search for and collect research results. Finally, this chapter describes corporate engineers' challenges and barriers when searching for and applying research results as reference system elements in their engineering activities.

Chapter 8 condensates all the previous findings to develop and present recommendations for the relevant stakeholders. These recommendations aim to improve the usability of research results as reference system elements in corporate product engineering. The recommendations address corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers.

Chapter 9 summarizes the main results of this thesis and presents the overall conclusion.

Chapter 10 closes this thesis by providing an outlook on further research needs and future research projects following this thesis.

2 Fundamentals and State of Research

The subject of this thesis is to improve the usability of research results as references in corporate product engineering. In the model of SGE – System Generation Engineering by Albers (formerly known as the model of PGE – Product Generation Engineering by Albers (Albers, Bursac, & Wintergerst, 2015)), references are existing (sub-)systems and the associated knowledge that serve as the basis and starting point for developing new systems (Albers, Rapp, et al., 2019). To clarify the research subject and to specify the research need, the following sections present the necessary fundamentals based on the current state of research. Since this thesis contributes to the KaSPro – Karlsruhe School of Product Engineering, the following sections also introduce core elements of the KaSPro. Section 2.1 creates an understanding of the term innovation in product engineering. Consecutively, Section 2.2 presents the process of product engineering. Section 2.3 dives into product engineering based on references. Finally, Section 2.4 discusses research results as potential reference system elements and their transfer.

2.1 Understanding of Innovation in Product Engineering

It is the task of corporate product engineering teams to contribute to the creation of innovation. However, the literature does not provide a consistent understanding of the term innovation (based on the Latin *innovatio*, meaning *renewal*). Isaksson et al. (2019) offer an up-to-date overview of the definitions of innovation from an engineering perspective. A common characteristic of these definitions is technical or organizational novelty (Garcia & Calantone, 2002; Isaksson et al., 2019). Some definitions, such as the one in Henderson and Clark (1990), consider the link to economic success as a separate element to innovation. However, Schumpeter (1927) already combined the technical and economic views as necessary aspects of an innovation. In this understanding of innovation as an economically successful novelty, the term invention describes the novelty itself. A core aspect of reaching an innovation as an economically successful novelty is to include customer needs early on and continuously (Cooper & Kleinschmidt, 1987). Albers (1994) also identified customer orientation as key to corporate success. Besides customer needs, Hippel (1986) stresses the importance of considering the users when developing innovation. Combining these aspects, an innovation realizes a number of benefits for customers, users, and the provider (Albers, Heimicke, et al., 2018). The engineering team's task is to identify, describe, and validate this so-called benefits bundle. Therefore, Albers, Heimicke, et al. (2018, p. 255) introduce the product profile as a “model of a [benefits bundle] that makes the intended provider, customer[,] and user benefits accessible for validation and explicitly specifies the solution space for the design of a [system] generation.” To realize the benefits bundle, the discussed aspect of novelty is added. Here, novelty is not limited to (subsystems of) mechatronic products but can also concern business models (Albers, Basedow, et al., 2020) and processes (Crossan & Apaydin, 2010).

Based on the aspects mentioned above, this thesis adopts the understanding of innovation according to Albers, Heimicke, et al. (2018), which is a central element of the KaSPro – Karlsruhe School of Product Engineering:

Definition 1: Innovation in Product Engineering

> “An innovation is the successful realization of a novelty, a creative idea or invention on the market with extended customer, user[,] and supplier benefits.”
> Glossary of the IPEK (2024) based on Albers, Heimicke, et al. (2018)

Figure 2.1 illustrates the understanding of innovation according to Albers, Heimicke, et al. (2018).

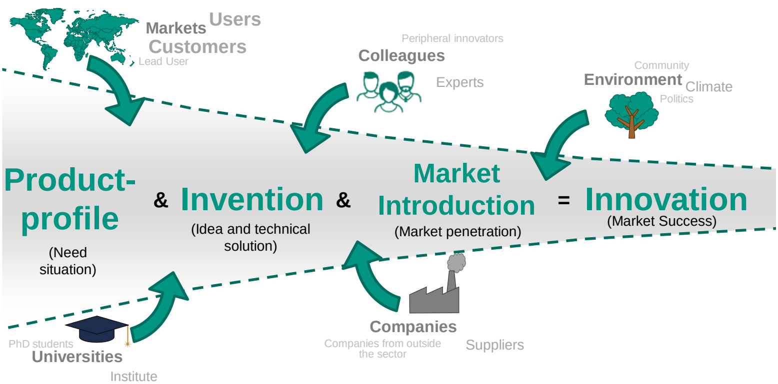


Figure 2.1: Elements of innovation based on Albers, Heimicke, et al. (2018).

It is the task of product engineers to conduct the necessary activities to realize innovation within product engineering. Thus, product engineering aims to transfer needs and objectives to products via analysis and synthesis activities (Pahl et al., 2007; VDI Verein Deutscher Ingenieure e.V., 2019b). Here, a product represents a combination of elements of a technical system, a service, and a business model (Albers, Basedow, et al., 2020). The VDI Verein Deutscher Ingenieure e.V. (2019b, p. 8) defines a product as a “material or immaterial commodity or service which is offered alone or as a system in order to satisfy the need of the market as well as the needs of users in a target-group-oriented way”.

Research offers valuable input for product engineering to create innovation, particularly in the aspect of invention (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017). Product engineers can use research results as references in product engineering. Before Section 2.3 discusses the role of references in product engineering and Section 2.4 sheds light on using research results as references in particular, Section 2.2 focuses on the state of research concerning product engineering processes.

2.2 Models to Describe Product Engineering Processes

Product engineering is a part of the product life cycle that includes strategic planning, product development and production system development (Albers & Gausemeier, 2012). The VDI 2221 uses product design as a synonym for product development. According to VDI Verein Deutscher Ingenieure e.V. (2019b, p. 8), product development is an “interdisciplinary corporate process used to design a marketable product, the process is based on the definition of initial objectives and requirements for the product which are constantly further improved and iteratively adjusted in the course of the process”. Furthermore, literature and practice often use the term product engineering as a synonym for product development, too (VDI Verein Deutscher Ingenieure e.V., 2019b).

A challenge to model product engineering processes is the uniqueness and individuality of each engineering process (Albers, 2010). Different engineering contexts and situations are two reasons for this uniqueness and individuality. The context and situation influence the successful selection and design of engineering projects, processes, and methods (Gericke et al., 2013). Here, engineering context describes the environment surrounding the engineering process. Contextual factors describe the context and influence the product and process (Meißner et al., 2005; Ponn, 2007). These factors determine how engineering activities can be conducted to achieve the targeted quality of engineering results (Gericke et al., 2013).

Additionally, Birkhofer et al. (2005) state that knowledge about the engineering situation is essential for successfully designing and conducting engineering processes and methods. Following Ehrlenspiel and Meerkamm (2017), the engineering situation describes the state at a point in time in the engineering process that can be described by the state of the product in development, the engineering process itself, and factors influencing the product and process. These factors can be, e.g., individual, group, and company-specific influences.

Multiple authors discuss factors influencing the engineering situation and context in literature (cf. Dziallas & Blind, 2019; Gericke et al., 2013; Guérineau et al., 2018; Koberg et al., 2003; Ponn, 2007; Wilmsen et al., 2019). By analyzing the relationship between the factors influencing the engineering situation and the engineering context, Wilmsen et al. (2019) discovered that the engineering situation represents a time-dependent subset of the factors describing the engineering context. Blessing and Chakrabarti (2009) define engineering as a dynamic and complex phenomenon. This phenomenon comprises humans, a system in development, the according processes, knowledge, methods, and tools in an organizational micro- and macro-economic context. Following Blessing and Chakrabarti (2009), all these aspects are subject to their own goals, structures, and cultures and direct different, time-dependent requirements towards product engineering. Thus, all must be considered when designing the optimal engineering situation (Blessing & Chakrabarti, 2009).

2.2.1 Product Engineering as an Iterative Problem-Solving Process

Following Albers et al. (2002), at its core, every product engineering process is a problem-solving process. According to Dörner (1979), a problem represents the deviation between an arbitrarily unknown actual state and a desired, initially vague target state. Here, the pass to reach the target state is partly unknown. Product engineering is a coevolutionary process that iteratively defines and develops the problem and creative solution (Dorst & Cross, 2001; Maher et al., 1996; Pahl et al., 2007). Thus, analysis and synthesis activities alternate each other towards a goal until the actual state matches the target state (Albers et al., 2002; Pahl et al., 2007; VDI Verein Deutscher Ingenieure e.V., 2019b).

Based on the system theory of engineering, according to Ropohl (1975), Albers (2010) extends the problem term and describes product engineering as the transfer of an initially vague system of objectives to a concrete system of objects via an operation system. Figure 2.2 illustrates the iterative coevolutionary development process of the systems of objectives and objects via the operation system.

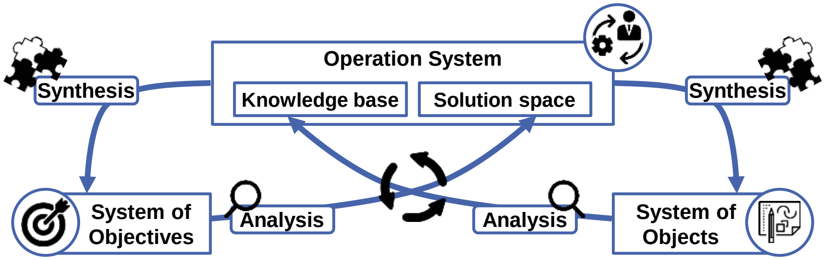


Figure 2.2: Iterative development of the systems of objectives and objects via the operation system through an alternation of synthesis and analysis activities (extended system triple of product engineering). Adapted from Albers et al. (2011)

The system of objectives contains all objectives, boundary conditions, their interactions, and justifications for the development of the system in development. The system of objects comprises the artifacts created in the engineering process, including the system in development itself. The operation system is a sociotechnical system that creates the systems of objectives and objects. It comprises all methods, processes, and resources required for the engineering process, including the engineers themselves. The operation system evolves and details the systems of objectives and objects iteratively through an alternation of synthesis and analysis activities. The process described by the system triple of product engineering can be observed on different levels, from individual engineers to complete organizations. (Albers et al., 2011)

The cognitive apparatus of product engineers is limited when it comes to problem-solving (Ehrlenspiel & Meerkamm, 2017). Thus, methods can support the engineers in all product engineering activities. Figure 2.3 provides an overview of methods for problem-solving sorted by their degree of detail and range of application.

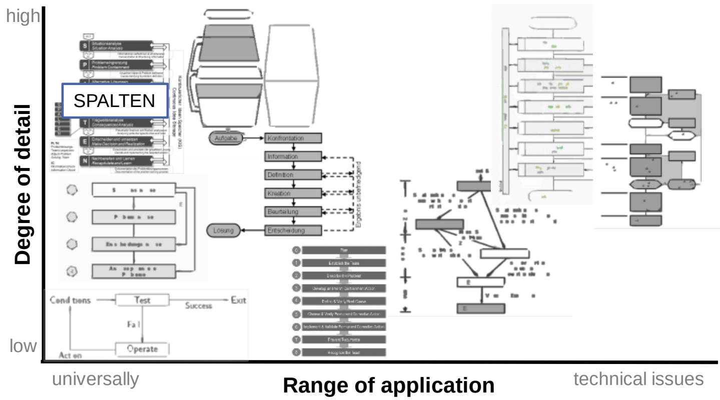


Figure 2.3: Overview of problem-solving methods sorted by their degree of detail and range of application. Adapted from Albers, Reiss, Bursac, and Breitschuh (2016)

To leverage the full potential of methods, they must be adjusted to the specific engineering situations (Birkhofer et al., 2005; Braun & Lindemann, 2003).

2.2.2 Product Engineering Process Models

Besides the complexity of products/ systems, the complexity of processes increases, too (Dumitrescu et al., 2021). For example, the increasing number of involved engineering disciplines or the geographic distribution of engineering teams increases process complexity. According to Wynn and Clarkson (2018), modeling these processes enables the processes' analysis, structuring, and improvement. In collaborative product engineering, a process model is necessary to describe the emerging phenomena of product engineering (Chui, 2002; Cicognani & Maher, 1997). Chui (2002) states that the process model is vital for all actors in the engineering process to understand their role and for researchers to analyze the product engineering activities. Figure 2.4 provides an overview of multiple process models with different degrees of detail and formalization following VDI Verein Deutscher Ingenieure e.V. (2019b).

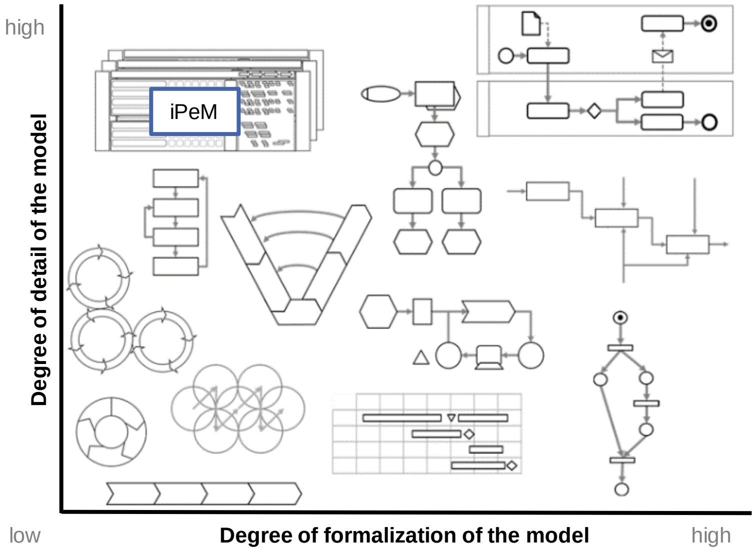


Figure 2.4: Overview of models to model product engineering processes sorted by their degree of detail and formalization. Adapted from VDI Verein Deutscher Ingenieure e.V. (2019b).

These models represent an idealized form of product engineering processes, which consist of individual, sometimes sequential steps with hierarchical phases, subordinate activities, and intermediate results of the process. (VDI Verein Deutscher Ingenieure e.V., 2019b).

The understanding of the system triple of product engineering and the problem-solving method SPALTEN (cf. subsection 2.2.1 and Albers, Reiss, Bursac, & Breitschuh, 2016; Albers et al., 2002) form the basis for the iPeM – integrated Product engineering Model (Albers & Meboldt, 2007). As a highly formalized meta-model, the iPeM enables to model engineering processes and offers a detailed orientation for the user through the description of micro and macro activities (Albers, Reiss, Bursac, & Richter, 2016; VDI Verein Deutscher Ingenieure e.V., 2019b). As shown in Figure 2.5, the iPeM offers multiple layers to enable the modeling of relations of product development with production system, validation system, and strategy development, as well as modeling multiple product generations (Albers, Reiss, Bursac, & Richter, 2016).

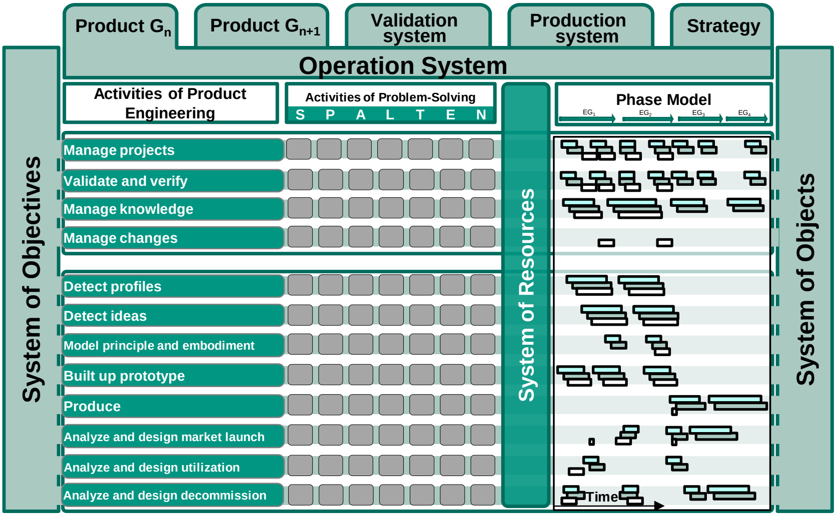


Figure 2.5: One layer of the iPeM – integrated Product engineering Model. Adapted from Albers, Reiss, Bursac, and Richter (2016).

The iPeM distinguishes and offers basic and core activities of product engineering as part of the operation system. Basic activities (manage projects, validate and verify, manage knowledge, and manage changes) are performed to support the core activities and continuously improve the product engineering process (Albers, Reiss, Bursac, & Richter, 2016). Core activities represent the activities that directly lead to increased product maturity (Reiss, 2018) (cf. Subsection 2.3.2 regarding maturity assessment). The subdivision into activities enables a manageable, rational, and industry-independent approach to both engineering and research (VDI Verein Deutscher Ingenieure e.V., 2019b). Additionally, VDI Verein Deutscher Ingenieure e.V. (2019b) stresses that the activities must be performed with varying intensity and suitable for both procedural and organizational structure.

The iPeM represents the actual planning, implementation, and execution of the activities in the phase model. Here, the execution of activities does not occur sequentially but often iteratively (VDI Verein Deutscher Ingenieure e.V., 2019b). However, flexibility and the ability to react to unforeseen events are essential, especially when developing complex products and when changes occur frequently during the product engineering process (Thomke & Reinertsen, 1998). The iPeM enables agile product engineering to address this flexibility and responsiveness.

2.2.3 Agility in Product Engineering

Agile approaches increase the responsiveness of development teams to dynamic changes in the engineering process (Albers, Heimicke, Spadinger, et al., 2019; Schwaber & Sutherland, 2020). Based on the understanding of the system triple of product engineering (cf. Subsection 2.2.1) and innovation (Section 2.1), Albers, Heimicke, Müller, and Spadinger (2019, p. 10) define agility as “the ability of an operation system to continuously check and question the validity of a project plan with regard to the planning stability of the elements in the system triple and, in the case of an unplanned information constellation, to implement a situation- and demand-oriented adaptation of the sequence of synthesis and analysis activities, whereby the customer-, user- and provider-benefits are increased in a targeted manner.”

Albers, Heimicke, Spadinger, et al. (2019) describe how agile development approaches are also increasingly being introduced in mechatronic product engineering. However, new challenges arise when transferring these approaches from software development[1]. ASD - Agile Systems Design, according to Albers, Heimicke, Spadinger, et al. (2019), presents a structuring approach for the agile development of mechatronic systems and the associated validation systems, production systems, and product strategy. The ASD approach serves as a guideline for developing and using methods and processes in product engineering (Albers, Heimicke, Spadinger, et al., 2019). Figure 2.6 shows the nine basic principles of the ASD approach.

[1] Agile approaches originally come from software development and are based on the Agile Manifesto according to Fowler and Highsmith (2001).

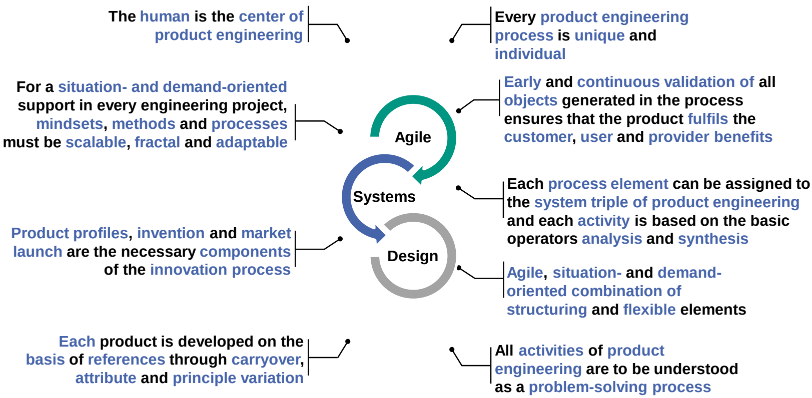


Figure 2.6: The nine basic principles of the ASD - Agile Systems Design according to (Albers, Heimicke, Spadinger, et al., 2019). Adapted from (Albers & Bursac, 2019).

Agile approaches are one answer to the challenges of the product engineering process of complex systems addressed in the Advanced Systems Engineering (ASE) concept and a core aspect of ASE.

2.2.4 Engineering of Tomorrow: Advanced Systems Engineering

Already in 2010, Albers and Gausemeier described research needs for transitioning from discipline-oriented product engineering to foresighted and system-oriented integrated product engineering. The concept of Advanced Systems Engineering (ASE) has been shaped in recent years to meet these research needs (cf., e.g., Albers & Lohmeyer, 2012; Albers et al., 2012). However, there is still a need for research concerning ASE and new interdisciplinary approaches to product engineering due to today's challenges in system development (Albers, 2023). Dumitrescu et al. (2021) define three fields of action in the ASE concept: Advanced Systems (AS), Systems Engineering (SE), and Advanced Engineering (AE).

Advanced Systems are characterized by a high degree of autonomy, dynamic networking, sociotechnical interaction, and a high degree of system complexity[2]

[2] For example, Weber (2005) describes five dimensions of complexity.

(Dumitrescu et al., 2021). This complexity increases further (Friedenthal et al., 2021), and global megatrends foster the development of advanced systems, which are often (part of) a system of systems[3] (Dumitrescu et al., 2021).

In ASE, Systems Engineering and Advanced Engineering approaches simultaneously enable and support the development of Advanced Systems (Dumitrescu et al., 2021).

The International Council on Systems Engineering (INCOSE) describes Systems Engineering in three dimensions: perspective, process, and profession. Systems Engineering is an interdisciplinary and iterative approach to the holistic engineering of sociotechnical systems across the whole product life cycle. (Walden et al., 2015) One manifestation of Systems Engineering is Model-based Systems Engineering (MBSE). MBSE is “the formalized application of modeling to support system requirements, design, analysis, and verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (Walden et al., 2015, p. 189). In contrast to traditional, document-based approaches, which spread information over multiple (text) documents, MBSE models all information in a central, interconnected, and interdisciplinary system model (Walden et al., 2015). This model-based centralization includes linking and using product models across multiple product engineering projects. Albers, Matthiesen, et al. (2015) provide a framework for product models that considers different application areas and varying levels of abstraction in modeling.

Advanced Engineering summarizes new processes, methods, and tools that extend current engineering approaches by using creativity, agility (cf. Subsection 2.2.3), and digitalization (Dumitrescu et al., 2021).

Another central pillar in Advanced Engineering is the understanding of the development of new systems as the development of new system generations to enable cross-generational system engineering (Albers, Dumitrescu, et al., 2022). The iPeM reflects this understanding of new products as a new system generation by integrating multiple product generation layers, and the principles of ASD state that all products are developed based on references, too. However, many common process models focus on a single product engineering project, with references to existing systems being, at best, implicit. The following section presents approaches

[3] For example, Albers, Mandel, et al. (2018) characterize a system of systems using nine dimensions.

explicitly describing the relationship between newly developed and already existing systems.

2.3 Developing New Systems Using References

“The ultimate aim of all […] efforts [of research groups working on design reuse] is to assist the designer to develop products that maximize customer satisfaction with minimal resources and cost and with minimal effort.”

– Sivaloganathan and Shahin (1999, p. 641)

While some authors in the literature distinguish products developed without any references (e.g., so-called original or novel designs) from products developed with references (e.g., evolutionary design) (Hamraz et al., 2013), Sivaloganathan and Shahin (1999) state that product development would always be a combination of already existing solutions and new innovations. Moving ahead, Wynn and Eckert (2017) discovered that many researchers consider product engineering an iterative process, even across products. This results in relationships between systems in development and already existing systems.

Alblas and Jayaram (2015, p. 6823) describe design reuse as “the process of using previous design artifacts in future designs”. Duffy et al. (1995) introduced the Design Reuse Model to operationalize this understanding. Similarly, King and Sivaloganathan (1998) present a Flexible Design Model as a strategy for design reuse with one existing product as the starting point. Introducing the Autogenetic Design Theory and the Technical Inheritance concept, Vajna et al. (2005) and Lachmayer et al. (2014) lean on the biological concept of evolution to describe engineering as an evolutionary process starting with objects of already existing systems. The concept of Engineering Change considers “changes and/ or modifications to released structure […], behavior […], function […], or the relations between functions and behavior […], or behavior and structure […] of a technical artefact” (Hamraz et al., 2013, p. 475).

However, none of the presented concepts manage to holistically model and support the relations between already existing systems and systems in development. For example, they focus on either a high or low degree of abstraction or focus on individual stages within the product engineering process. The model of SGE – System Generation Engineering by Albers approaches these shortcomings by incorporating the hierarchical and structural concept of the system theory of engineering (c.f. Ropohl, 1975) and defining different variation types to describe the relations between existing systems and a system in development. The following section presents the model of SGE – System Generation Engineering.

2.3.1 The Model of SGE – System Generation Engineering: A Model to Describe the Development of Products in Generations

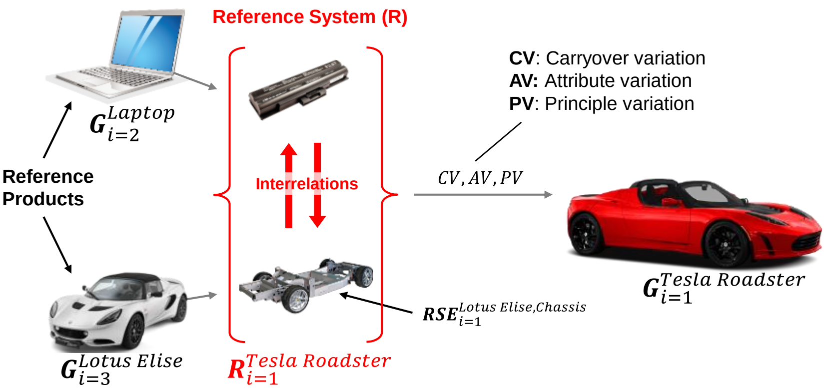
The model of SGE – System Generation Engineering enables the description of fundamental phenomena in the development of systems (Albers, Bursac, & Wintergerst, 2015; Albers & Rapp, 2022). The understanding of the model of SGE enables the development of new methods, processes, and tools for product engineering (Albers, Bursac, & Wintergerst, 2015). Therefore, the model of SGE uses two basic hypotheses to describe the development of new systems:

- The development of new systems is always based on references. These references are elements of the reference system (R) (Albers, Bursac, & Wintergerst, 2015).
- Three types of variation can describe the development of new systems based on the reference system: carryover variation (CV), attribute variation (AV), and principle variation (PV) (Albers, Bursac, & Wintergerst, 2015).

In carryover variation, an element of the reference system is carried over into the new system generation, with the interior of this element considered a “black box”. Adjustments are made at the interfaces according to system integration requirements and boundary conditions. In attribute variation, the internal connections of the element of the reference system are retained in the new system generation. Thus, the solution principle remains unchanged compared to the reference system element. However, the attributes of the element are varied. In principle variation, the solution principle of the reference system element is altered. (Albers, Bursac, & Wintergerst, 2015; Albers, Fahl, et al., 2020)

Figure 2.7 schematically illustrates the basic hypotheses of the model of SGE.

The model of SGE can be applied both to describe different system generations and their relation to elements of the corresponding reference system and to provide a more detailed description of the development within a system generation. Here, the model of SGE can be used to describe various development increments with increasing maturity during the development of a system generation (Albers & Rapp, 2022). These intermediate generations are called "engineering generation (E)" (Albers, Fahl, et al., 2020).



G_i: System Generation i; R_i: Reference System of System Generation i; **RSE**$_i$: Reference System Element of R_i

Figure 2.7: Exemplary schematic representation of the use of the model of SGE to describe the development of the Tesla Roadster. Adapted from (Albers, Rapp, et al., 2019).

Mathematically, a new system generation is the sum of subsystems developed through the three types of variations (Albers, Bursac, & Wintergerst, 2015). Using the extended nomenclature, information regarding the product line, variant, or specific customers or users can be expressed for a system generation G or an engineering generation E, as well as the respective reference system R (Albers, Fahl, et al., 2020):

$$G_i^{\{product\ line,\ variant,\ customer,\ user,\ \dots\}}\ with\ i \in \mathbb{N}.$$

$$E_{i,j}^{\{product\ line,\ variant,\ customer,\ user,\ \dots\}}\ with\ i,j \in \mathbb{N}.$$

$$R_{i(,j)}^{\{product\ line,\ variant,\ customer,\ user,\ \dots\}}\ with\ i,j \in \mathbb{N}.$$

Here, i represents the number of the system generation, and j represents the number of the engineering generation. If $i = n\ (G_{i=n})$, it represents the system generation in development that will be introduced to the market next. R_i reflects the reference system of the system generation G_i. Consequently, $R_{i,j}$ reflects the reference system of the engineering generation $E_{i,j}$ of the system generation G_i. Albers, Kürten, et al. (2022) describe the role and development of the reference system in different engineering paths, starting from research projects via advance engineering and serial engineering projects to modular engineering kit projects.

The reference system comprises already existing elements. These elements can be the complete systems or subsystems of predecessor system generations or competitor's systems, systems from different industries, systems of R&D projects, or systems from university research (Albers, Bursac, & Wintergerst, 2015). The reference system evolves throughout the complete engineering process (Albers, Rapp, et al., 2019). Albers, Rapp, et al. (2019) define the reference system as follows:

Definition 2: Reference System

"The reference system for the development of a new [system] generation is a system whose elements originate from already existing or already planned socio-technical systems and the associated documentation and are the basis and starting point for the development of the new [system] generation." (Albers, Rapp, et al., 2019, p. 1699)

Following this understanding, the development of an completely new system or sub-system represents an edge case within the model of SGE where $i = n = 1$ (G_1). In this case, the corresponding reference system (R_1) lacks a predecessor generation, as none exists. Consequently, the development of a G_1 starts without a direct reference product architecture. Nevertheless, R_1 still incorporates other elements, which may originate from within and/ or outside the organization. (Albers, Bursac, & Wintergerst, 2015)

Using the information about the origin of reference system elements and the new development share (sum of the attribute and principle variation share) in the system in development, Albers, Rapp, et al. (2017) developed a risk portfolio to estimate engineering risks in early phases of the product development. Figure 2.8 shows the risk portfolio.

Depending on the "distance" to the engineering team's expertise, the knowledge regarding the reference system elements tends to decrease. The technical novelty tends to increase with the increase in the share of new development. Both factors tend to increase the risk within engineering. (Albers, Rapp, et al., 2017)

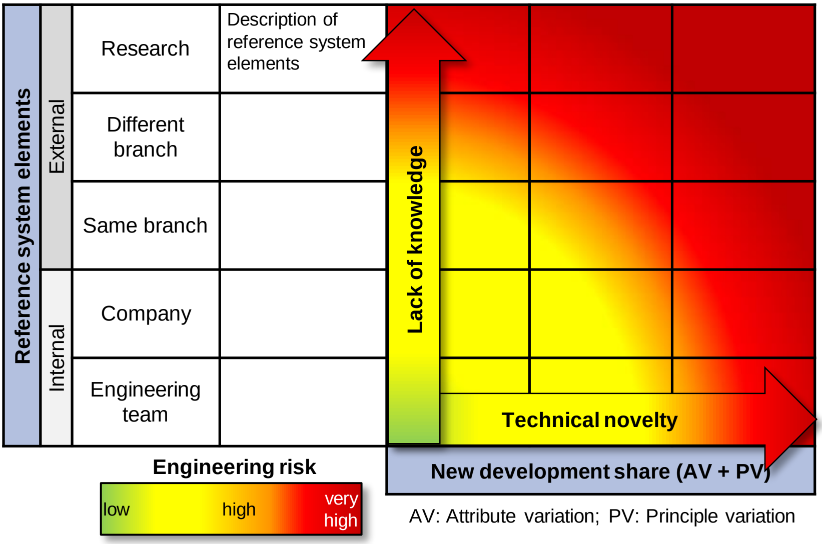


Figure 2.8: Risk estimation using the model of SGE: The analysis of the reference system elements and planning of the new development shares allow an early estimation of the engineering risk. Adapted from Albers, Rapp, et al. (2017).

Compared to the other approaches using references implicitly or explicitly, beyond the pure description, the model of SGE provides mathematically justified instructions for working with elements of a reference system through the types of variation. A recent cornerstone in this regard is the work of Rapp (2021). This formalization is particularly relevant for engineering approaches in Advanced Engineering and Systems Engineering, especially when using Model-based Systems Engineering and, thus, key for the successful development of Advanced Systems (cf. Subsection 2.2.4). Especially when using external references, a maturity assessment is essential. The following section presents the concept of Technology Readiness Levels for maturity assessment.

2.3.2 Maturity Assessment Using the Technology Readiness Levels

Weinzierl (2006) describes product maturity as the level of fulfillment of requirements for a product. Paetzold (2006) explicitly includes the customer and provider views using two of the three dimensions of the benefits bundle (cf. Section

2.1) to define the requirements. A well-accepted approach to assessing maturity are the Technology Readiness Levels (TRL) developed by Mankins (1995). As shown in Figure 2.9, Mankins (1995) defines nine levels to rate a technology's maturity.

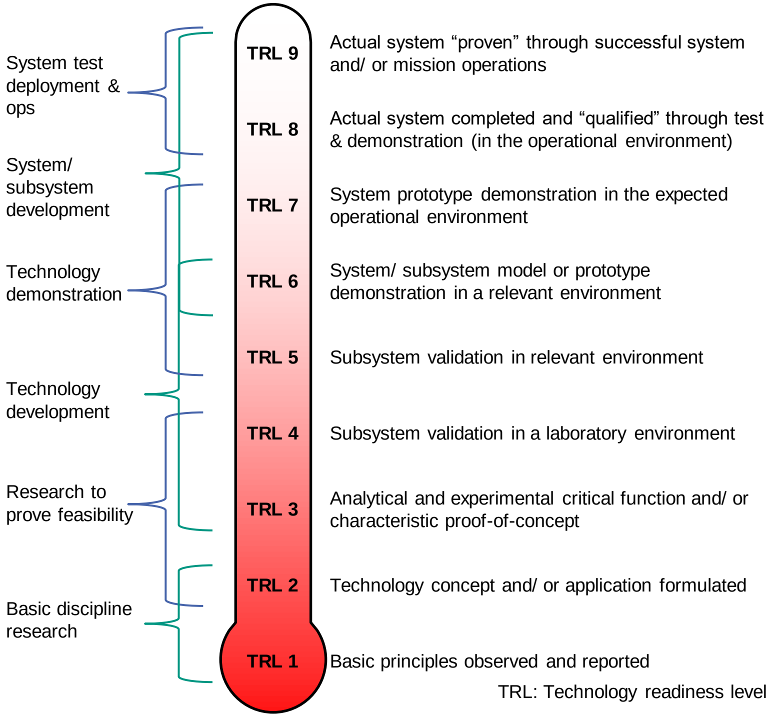


Figure 2.9: Nine technology readiness levels to rate the maturity of technology. Adapted from Mankins (2009).

However, one limitation of the TRL concept for maturity assessment of technologies is the neglect of influences and interactions with other technologies within the overall system (Sauser et al., 2009). Sauser et al. (2010) introduce the Integrated Readiness Level (IRL) concept to consider the interactions of different subsystems, too. Similarly to the IRL scale, Behdinan et al. (2017) introduce the Design Readiness Level (DRL) concept based on the TRLs. To lift the TRLs from a qualitative to a quantitative scale, Fahimian and Behdinan (2017) used the development time from the start of the project to reach the respective TRL to calculate cardinal coefficients based on a quantitative value (development time). Revfi et al. (2020) extend these concepts to apply DRLs to multi-material concepts.

Connecting the concept of TRLs and the understanding of the system triple of product engineering (cf. Subsection 2.2.1), Richter, Troester, et al. (2020) developed a description, visualization (Richter, Felber, et al., 2020), and process model (Richter, Schmidt, et al., 2020) to advance the system in development's maturity systematically.

While the readiness levels serve to assess the maturity of technologies or designs, university research produces a lot of knowledge and technologies. These research results can serve as potential reference system elements in product engineering. The following section discusses research results as reference system elements and approaches for knowledge and technology transfer.

2.4 Using Research Results as References in Product Engineering

The prime source for reference system elements is the experience of the engineering team members, especially from previous projects of the engineers (Ahmed et al., 2003; Shahin et al., 1999). As presented, Albers, Bursac, and Wintergerst (2015) identified predecessor system generations, competitor systems, systems from different industries, and systems from university research as potential sources for reference system elements (cf. Subsection 2.3.1). Hajialibeigi (2021) systematically describes four potential sources for reference system elements. These sources are the vertical (suppliers, private clients, public clients), horizontal (competitors), societal (consultants, government, private research institutes, professional associations), and specialized class (universities, conferences, scientific journals). Albers, Rapp, et al. (2017) distinguish between internal (engineering team, company) and external (same branch, different branch, research) sources for reference system elements. Due to its novelty, knowledge and technologies developed in research are precious reference system elements offering potential competitive advantage as input for an invention (cf. Section 2.1) (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017). Albers (2018) describes the role of research in terms of product engineering by providing expertise and references to companies. Companies, in turn, use this expertise and reference system elements from research to develop and offer technological solutions to the needs of society.

2.4.1 Knowledge and Technologies: The Results of Research

David et al. (1992) distinguish between the results of basic and applied research. While basic research aims to increase the understanding of subjects or natural phenomena, applied research focuses on the “creation of specific applications with economic value” (David et al., 1992, p. 74). Albers (2018) follows this understanding and distinguishes basic and applied research based on the realization horizon. Relating the research output to social benefit, David et al. (1992, p. 76) define three types of research results: Outputs with

- “information […] that may be applied directly to the creation of new processes or products.”
- “information […] that is an input into other basic and applied research activities and, with modification and refinement, forms the basis for new products or processes.”
- “information to improve processes or products that are primarily based on other scientific or technological discoveries”.

Bakouros and Samara (2010, p. 146) distinguish “scientific and technological information (which can increase the efficiency of applied R&D in industry […]), equipment and instrumentation (used by firms in their production processes or their research), skills or human capital (embodied in students and faculty members), networks of scientific and technological capabilities (which facilitate the diffusion of new knowledge), and prototypes for new products and processes as the results of research. The results can manifest in different formats such as articles, proceedings, prototypes, computer software, or patents (cf., e.g., (European Commission; Marcondes, 2012; Mutz et al., 2012)).

Technology transfer considers the commercialization of “technologies”. One part of this technology transfer is the transfer of technologies resulting from research into corporate product engineering. According to Buratti and Penco (2001), the term technology is traditionally used for hardware or physical systems, but the recipient needs an understanding of the technology. Thus, technology is always linked to the necessary knowledge and skills required to eventually utilize the technology independently of the original provider (Baranson, 1970). The needs and capabilities of the potential technology users play an essential role (Buratti & Penco, 2001). The following section discusses the transfer of research results as reference system elements into corporate product engineering.

2.4.2 Knowledge and Technology Transfer: Research to Companies

The literature repeatedly emphasizes the importance of knowledge transfer and management (cf., e.g., Nonaka & Takeuchi, 1995; North, 2016; Ponn & Lindemann, 2005; Weber & Husung, 2016). Among other areas, Engineering Change Management focuses on the knowledge transfer from the development of already existing systems to the development of new systems. It stresses the role of humans who participated in the former engineering project (cf., e.g., (Clarkson et al., 2001; Flanagan et al., 2007; Specht, 2018)). Various approaches exist for knowledge transfer within companies, such as in Engineering Change Management (cf., e.g., (Ahmad et al., 2013; Clarkson et al., 2001; Langer et al., 2012; Stenholm et al., 2019)), reference product models (cf., e.g., Albers, Matthiesen, et al., 2015; Albers, Scherer, et al., 2015), or design and solution patterns (cf., e.g., Albers & Deigendesch, 2010; Weber & Husung, 2016).

Another type of knowledge and technology transfer occurs between academic research and corporate product engineering. Leveraging university research results can offer valuable input to solve, i.a., technical challenges (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017).

Technology transfer is a multifaceted process involving diverse stakeholders with varying views on the value and potential applications of the technology (Wahab et al., 2011). Johnson et al. (1997) describe technology transfer as encompassing the entire journey of the technology, from its discovery in research to its end-user adoption. Based on Kim (1990), Buratti and Penco (2001, p. 36) describe “technology transfer [as] every process that aims at transferring technological know-how from [a] donor – e.g., a university, a research center[,] or R&D departments of firms; to one or more: recipients – firms which may either directly use or co-develop the technology”. Due to the complexity of the transfer process, Buratti and Penco (2001) add a third party to the process. Institutions such as public agencies or science parks act as an intermediate between the donors and recipients (Buratti & Penco, 2001). Here, a technology transfer office (TTO) is a unit often within universities for technology commercialization (Carlsson & Fridh, 2003).

Rogers (2002) offers a broader view of technology transfer, defining it as the practical application of information that encompasses the technology itself. Technology transfer is a two-way communication process in which researchers convey technological inventions to users within recipient organizations. These users may then commercialize the invention within a product or service. (Rogers, 2002) Thus, from the corporate product engineering view, technology transfer reflects the inclusion of reference system elements from research into the engineering process of a system. Goebel et al. (2024) cluster technology transfer from universities to industry into three categories based on Upstill and Symington (2002). The first way of technology transfer is the noncommercial transfer via, e.g., publications, presentations, or direct exchanges. The second way is a commercial transfer via, e.g., collaborative research formats, licensing and sale of intellectual property, or consulting services. The third way is via spin-offs (new companies). (Goebel et al., 2024; Upstill & Symington, 2002) However, all three ways of technology transfer focus on the donor perspective and how to support them in “commercializing” the technology.

2.4.3 Challenges in Using Research Results in Product Engineering

General issues of using existing systems as references are the identification, organization and representation, and extraction of design information of references (Iyer et al., 2005; Sivaloganathan & Shahin, 1999). In terms of using research results as references in product engineering, Bruneel et al. (2010) lament that there is an underrepresentation of studies investigating the barriers and measures to approach these. Bruneel et al. (2010) distinguish orientation-related barriers related to the differences between companies’ and universities’ goals and transaction-related barriers. These are related to university administration and Intellectual property issues. After an extensive literature review, Kleiner-Schaefer and Schaefer (2022, p. 877) condense four clusters of barriers: “[insufficient] R&D capability, lack of external support structures, mismatch with collaboration partners[,] and administrative barriers”.

Specific challenges that hinder using research results are, e.g., linked to Intellectual Property (IP) issues or unrealistic licensing expectations (Bruneel et al., 2010; Hall et al., 2001). A part of the IP issues can be the publication strategies of universities (Bruneel et al., 2010; Hall et al., 2001). A both-sided lack of understanding causes information loss and misunderstanding in communication (Bruneel et al., 2010). Researchers and engineers do not speak the same “language” (Guerrero et al., 2019). The mismatch in corporate and research goals and a lack of information can also reduce trust in the research results (Kleiner-Schaefer & Schaefer, 2022; Oliver et al., 2020). The long development times in research lead to mismatches with corporate expectations (Bruneel et al., 2010; Guerrero et al., 2019; Kleiner-Schaefer & Schaefer, 2022). Also, internal company obstacles can hinder using research results as references. A rigidity against novelties or the lack of qualification are such barriers (Guerrero et al., 2019; Kleiner-Schaefer & Schaefer, 2022).

Section 7.4 presents an own study of the challenges faced by corporate product engineers when using references from research based on the current state of research.

2.5 Conclusion

Section 2.1 introduces the state of research by providing an understanding of innovation in product engineering, which forms the basis of this thesis. It highlights university research's role in delivering input to create an invention.

Product engineering process models support structuring, managing, and executing engineering projects. Section 2.2 explains the importance of providing situation and context-adapted support as both influence the successful design, selection, and execution of engineering activities (Birkhofer et al., 2005; Gericke et al., 2013). The respective influencing factors from the engineering situation and context are highly relevant and must be identified to support the meaningful design of the reference system and the selection of suitable research results as reference system elements. Due to the increasing complexity of the systems to be developed and the engineering processes (Dumitrescu et al., 2021), Advanced Engineering approaches and Systems Engineering are necessary to develop Advanced Systems successfully. Model-based Systems Engineering plays an essential role in Systems Engineering to keep mastery over the increasing complexity and to enable the reuse of models and designs in engineering (Albers, Matthiesen, et al., 2015; Walden et al., 2015). Developing new systems in generations is vital to leveraging the potential of model reuse. Therefore, a (MB)SE-conform description of the reference system is pending.

As discussed in Section 2.3, several concepts describe and support product engineering as the development of new systems based on references. While some of these concepts focus on specific aspects such as, e.g., the reuse of shapes (Iyer et al., 2005), the model of SGE – System Generation Engineering provides a solid basis to describe the development of any new system based on any type of reference system element (Albers, Bursac, & Wintergerst, 2015). Furthermore, with its mathematical soundness, the model of SGE is a promising starting point for developing Advanced Engineering supports. However, while the model of SGE clearly relates the reference system and the respective system in development, the internal structure and design of the reference system are not defined in detail. A sound definition forms the basis for model-based applications in Advanced Systems Engineering. While the definition of the reference system describes what elements form the reference system (Albers, Rapp, et al., 2019), the concrete search for and collection of reference system elements is not described in detail in the model of SGE or the iPeM as the respective product engineering process model. Thus, there is a lack of understanding and support in designing and modeling a suitable reference system systematically within product engineering processes.

Research results represent potential reference system elements with great potential for product engineering (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017). As shown in Section 2.4, technology transfer is a well-established research field investigating the transfer of research results to commercialization (Johnson et al., 1997; Rogers, 2002; Wahab et al., 2011). However, the research interest focuses one-sidedly on the university's point of view of commercializing their research results. Technology transfer research neglects the search of product engineers for research results as reference system elements and their support. Thus, knowledge about barriers to using research results as reference system elements is also pending (Bruneel et al., 2010). The focus of the research on barriers is on industry-academia collaboration formats (cf., e.g., (Bruneel et al., 2010; Guerrero et al., 2019; Hall et al., 2001; Kleiner-Schaefer & Schaefer, 2022; Oliver et al., 2020)). While some of the barriers to the collaboration of product engineers and researchers might also affect the use of research results as reference system elements, the specific challenges remain in the dark. Thus, there is a lack of methodical support for searching and collecting research results from a product engineer’s point of view.

3 Research Need and Research Objective

This chapter deduces the research need, drawing upon the current state of research in Section 3.1. Subsequently, Section 3.2 derives this thesis' research objective based on insights gained from observations of engineering practice in corporate environments and the context of the thesis. Section 3.3 explains the basic assumptions needed to reach the objective. Finally, Section 3.4 operationalizes the research objective by formulating pertinent research questions.

3.1 Research Need

The increasing complexity and shortening development cycles of advanced systems necessitate the evolution of standard engineering practices to facilitate advanced engineering (Dumitrescu et al., 2021). The key to advanced engineering – and thus the enabler of advanced systems – is the effective management of knowledge and existing technologies and (sub-)systems that form the basis of engineering activities and system development (Albers, Dumitrescu, et al., 2022).

The current state of research offers different approaches to knowledge and technology management and modeling in engineering. Approaches and models explaining the relation of reference system elements and the (sub-)system in development, such as the model of SGE – System Generation Engineering, are present in the literature and accepted in the design research community (cf. Section 2.3). However, the engineering situation's and context's influences on the reference system are not yet well understood. Many methods and tools exist to search for and gather reference system elements, yet a systematic approach to compiling a suitable reference system is still missing. Systems engineering and tools such as MBSE – Model-based Systems Engineering can be used to model reference systems and thus make the reference system accessible for Advanced Engineering approaches. Advanced Engineering relies highly on approaches that enable and support the development of new systems as new system generations (Albers, Dumitrescu, et al., 2022). However, the internal structure of the reference system has not yet been described, but it is vital for modeling the reference system with MBSE.

The synthesis of the reference system is a highly complex and creative process (Albers & Düser, 2023) depending, e.g., on the engineering team's experience

(Ahmed et al., 2003; Shahin et al., 1999), which is not yet sufficiently understood and supported. However, the synthesis is crucial for efficient and effective engineering activities and ultimately for developing new successful system generations. Therefore, it is essential to identify and address the challenges in synthesizing the reference system to minimize potential negative impacts on the efficiency and effectiveness of engineering activities. Tackling these challenges is vital to utilizing the full potential of system generation engineering, maximizing the efficiency and effectiveness of engineering activities, and developing successful new system generations.

Systematic management of the reference system must be established in product engineering to mitigate these challenges and leverage the associated potential. Thus, exploring and analyzing the fundamentals and activities of reference system management and developing methodological support is imperative. These objectives form the overarching research goal to which this thesis and the according research activities contribute:

Establishment of RSM – Reference System Management as a core aspect of product engineering to improve the development of successful products.

RSM – Reference System Management describes the initial and continuous synthesis and analysis of the reference system. It organizes the interaction between the engineering team and the reference system. The goal of the activities of reference system management is to efficiently provide a well-suited reference system as "the basis and starting point for [developing a] new [system] generation" (Albers, Rapp, et al., 2019, p. 1699). Here, the synthesis of the reference system is a particularly complex process (Albers & Düser, 2023).

However, due to its complexity, establishing RSM in its totality is an endeavor too grand to accomplish within a single research project or doctoral thesis (for a more detailed derivation, see Chapter 5). Consequently, a more focused research objective must be defined for this thesis.

The author prepared this thesis as a member of the International Research Training Group (IRTG) "Integrated engineering of continuous-discontinuous long fiber reinforced polymer [(CoDiCoFRP)] structures" (IRTG 2078[1]) of the German Research Foundation (DFG). The main research goal of the IRTG is "to develop

[1] German: GRK 2078 (Graduiertenkolleg)

robust integrated engineering strategies for materials design as well as for structure and process optimization of CoDiCoFRP" (Böhlke et al., 2018, p. 5)[2]. Within the IRTG, transferring the researched and developed knowledge and technologies from the research level to industrial application was identified as a major challenge. Therefore, this thesis aims to research and develop "recommendations for industrial application" (Böhlke et al., 2018, p. 16) [3] and to "improve the applicability of the resulting knowledge [and technologies]" (Böhlke et al., 2018, p. 33)[4].

Technology and knowledge transfer from research to corporate product engineering is highly relevant because major societal challenges such as in the fields of climate change, energy supply, and demographic shift and all their consequences also need technical solutions. Collaboration between research and corporate engineering is crucial for developing and introducing these technical solutions to the market. Moreover, the efficient use of research results in corporate product engineering is a critical success factor for both economic success and technological progress in general. (Bauernhansl & Nestler, 2015; EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017)

The state of research regarding the relations of references and the development of new systems describes these relations, supports the development of the new systems based on the references, and makes this phenomenon accessible for research (cf. Section 2.3). The state of research regarding knowledge and technology transfer focuses on commercializing research results from the university's or researcher's point of view or on collaborative university-company projects (cf. Section 2.4). However, the literature does not cover the systematic support of individual product engineers of engineering teams in developing their reference system[5]. Identifying and using research results as reference system elements is still challenging for corporate product engineers. These challenges can hinder technological progress and negatively impact the advancement of engineering processes. (Bauernhansl & Nestler, 2015; EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007) Thus, the present challenges must be further analyzed, additional ones identified, and ultimately addressed to

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[2] Approved research proposal (unpublished)
[3] Approved research proposal (unpublished)
[4] Approved research proposal (unpublished)
[5] There are case studies that analyzed the used reference system elements retrospectively. Cf., e.g., Albers, Bursac, and Rapp (2017); Albers, Haug, et al. (2016); Albers, Rapp, et al. (2019).

better utilize the potential of research results by corporate product engineers to advance engineering processes and technological progress.

To verify the identified research need, this thesis conducted a study with 22 corporate product engineers from collaborative projects within the PDA_ASE initiative funded by the German Federal Ministry of Education and Research (BMBF)[6]. In this study, the participants were asked to provide their assessment of statements regarding the potential and actual use of research results in their engineering activities based on a five-point Likert scale. Appendix A details the composition of the participants. The results of this study were published at a scientific conference as specified (Kempf, Rapp, & Albers, 2022).

As illustrated in Figure 3.1, the study results show that many corporate product engineers recognize the unexploited potential of research results on the technological advancement in new system generations, improvement of their engineering processes, and competitivity of the overall company. The diversity in the participants' responses leads to the conclusion that the potential of research results is perceived individually. However, between 70-80% of the participants recognize unexploited potential in some engineering situations. None of the participants disagree completely and see no potential for using research results in product engineering. (Kempf, Rapp, & Albers, 2022)

[6] Within the initiative "Handling the complexity of sociotechnical systems – a report on Advanced Systems Engineering for the value creation of tomorrow (PDA_ASE)" of the "Innovations for Tomorrow's Production, Services, and Work" research program of the BMBF, the BMBF is funding nine collaborative projects of corporate and research partners.

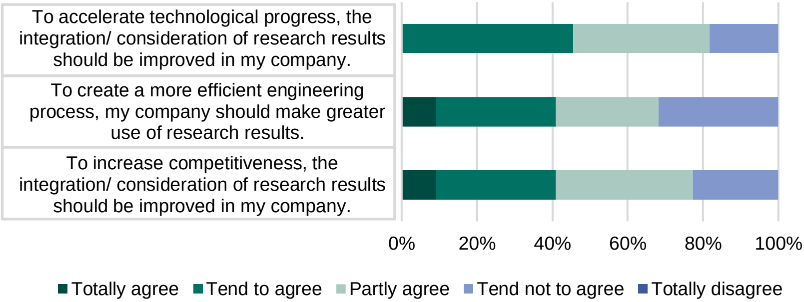


Figure 3.1: Evaluation of responses (n = 22) to statements regarding the potential of research results on improving and advancing their system in development, engineering processes, and competitive position. In all categories, most participants agree at least partly on the unexploited potential of research results in their companies. Adapted from Kempf, Rapp, and Albers (2022).

Exploring reasons for the unexploited potential, the survey shows that a great effort is often necessary to find suitable research results and use these results within corporate engineering activities. Approximately 50% of the participants agree that finding suitable reference system elements in research takes great effort. Even more (~60%) agree that using the identified reference system elements in their engineering activities requires a great effort. These results lead to the conclusion that it is challenging for many corporate product engineers to find suitable research results and use them within their engineering activities.

Asking for the support they receive for searching and applying reference system elements in research, Figure 3.2 shows that only approximately 50% of the participants state that they receive enough support when searching for reference system elements in research. Less than 20% state that they receive enough support in all situations. Thus, more than 80% see a lack of support in at least some situations. Only approximately 30% of the participants stated that they know what to consider when using reference system elements from research within their engineering activities. Approximately 35% of the participants are not entirely sure. In comparison, almost 40% of the participants stated that they do not know what to consider when using reference system elements from research. (Kempf, Rapp, & Albers, 2022)

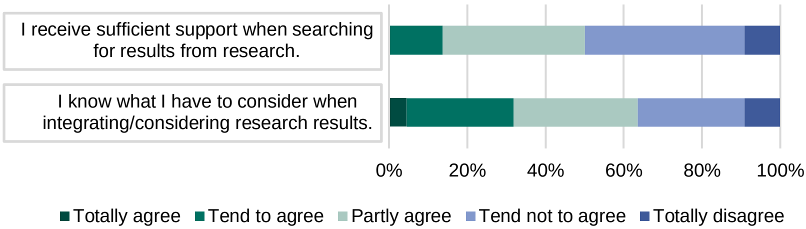


Figure 3.2: Evaluation of responses (n = 22) regarding the available support in searching research results and using them in a corporate context shows great challenges and confirms the need for support. Adapted from Kempf, Rapp, and Albers (2022).

Finally, Figure 3.3 shows that more than 80% of the participating corporate product engineers want to use reference system elements from research more often, at least in some situations, as ~80% agree at least partly (Kempf, Rapp, & Albers, 2022).

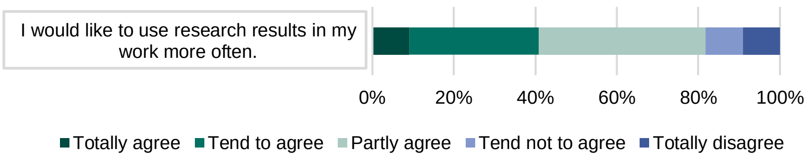


Figure 3.3: Evaluation of responses (n = 22) regarding a willingness to use reference system elements from research more often shows a broad wish to use more reference system elements from research. Adapted from Kempf, Rapp, and Albers (2022).

In summary, this study leads to the conclusion that there is a need to improve the usability of research results as reference system elements in corporate product engineering to leverage the potential of research results to advance the system in development.

This need aligns with the overarching research goal of establishing reference system management as formulated above. Research is a source for reference system elements that offers highly diverse elements spanning all complexity levels. Thereby, it qualifies to research and develop RSM – Reference System Management exemplarically. Follow-up research projects can start on this basis to research additional aspects of RSM – Reference System Management. Thus, this thesis focuses on establishing the field of research results as reference system elements as one core aspect of reference system management.

3.2 Research Objective

This thesis aims to develop the field of research results as possible usable reference system elements for corporate product engineering as one core aspect of RSM – Reference System Management.

The following sub-objectives have to be addressed to reach this objective:

- Analysis of the different types of research results and their characteristics. The different types of research results shall be classified according to their characteristics.

- Analysis of the current usage of research results as reference system elements in corporate product engineering. A particular focus shall be on the reasons, challenges, and methods for using research results as reference system elements in corporate product engineering.

- Development of recommendations for corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers to increase the usability of research results as reference system elements in corporate product engineering.

To achieve these objectives, this thesis introduces RSM – Reference System Management by using the example of the field of research results to the KaSPro – Karlsruhe School of Product Engineering. Developing the field of research results as possible usable reference system elements for corporate product engineering offers the foundation for fellow researchers to develop methodical support for the knowledge and technology transfer from research into companies. The recommendations given are already the first step to improving this transfer.

In the context of this thesis, research and research results describe the following:

Definition 3: Research and research results

Research refers to the activities conducted in research facilities. Research facilities include university and non-university research facilities such as the Fraunhofer Society or Max Planck Society facilities. Accordingly, research results are the outcomes of these research facilities' activities. This understanding does not consider corporate research departments' activities and results.

3.3 Basic Assumption

This thesis is based on the assumption that the model of SGE – System Generation Engineering can be used to describe the development of new system generations based on a connected reference system. Consequently, the model of SGE can also be applied to describe the use of research results as reference system elements.

> The model of SGE – System Generation Engineering can be used to describe the usage of research results as reference system elements for developing new product/ system generations.

3.4 Research Questions

Based on the research need and basic assumption presented, the following research questions structure this thesis to achieve the formulated research objective:

RQ1. What are the fundamentals of the reference system within the model of SGE – System Generation Engineering?

RQ2. How can research results be classified to facilitate their exploration as reference system elements in corporate product engineering projects?

RQ3. How do corporate product engineers search for and apply reference system elements from research, and what challenges do they face in this process?

RQ4. What are suitable recommendations to improve the usability of research results as reference system elements in corporate product engineering?

The following chapter presents this thesis's research approach to answer the research questions.

4 Research Approach

This chapter presents the research approach to reach the aforementioned research objective and answer the research questions. Therefore, this thesis followed an approach based on the Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009). Section 4.1 sets this thesis into the DRM framework and presents this thesis' structure. Section 4.2 introduces the research methods used and the research environment of the studies.

4.1 Research Stages and Structure of the Thesis

Product engineering is a highly complex process. According to Albers (2010), every engineering project is unique and individual. The DRM, as described by Blessing and Chakrabarti (2009), provides a framework to support researchers in studying the product engineering phenomenon. DRM enables the "formulation and validation of models and theories about the phenomenon of design, as well as the development and validation of support founded on these models and theories, in order to improve design practice, management, education[,] and their outcomes" (Blessing & Chakrabarti, 2009, p. 9). The DRM consists of four consecutive but iterative stages: Research Clarification (RC), Descriptive Study I (DSI), Prescriptive Study (PS), and Descriptive Study II (DSII) (Blessing & Chakrabarti, 2009).

Figure 4.1 presents the structure of this thesis' investigations following the DRM framework, including the corresponding chapters. It illustrates the methods used and results achieved in this thesis.

Chapters 1, 2, and 3 cover the *Research Clarification* of this thesis. These chapters motivate and deduce the research objective based on the overarching research goal. Therefore, the thesis analyzes the state of the research and conducts its own empirical study to validate the research objective within these chapters. The research object under investigation is developing the field of research results as possible usable reference system elements for corporate product engineering as one core aspect of RSM – Reference System Management.

Chapters 5, 6, and 7 cover the *Descriptive Study I* of this thesis. On the one hand, Chapter 5 analyzes and describes general core aspects of the reference system's fundamentals in three studies. These investigations are necessary to pursue this thesis' research objective but are not limited to its research object. On the other hand, Chapters 6 and 7 aim to gain an in-depth understanding of the current situation of engineers using research results as reference system elements in corporate product engineering. Chapter 6 analyzes and classifies the different types of usable research results, and Chapter 7 analyzes the triggers and methods for using research results, and identifies the challenges and barriers of using research results as reference system elements in corporate product engineering.

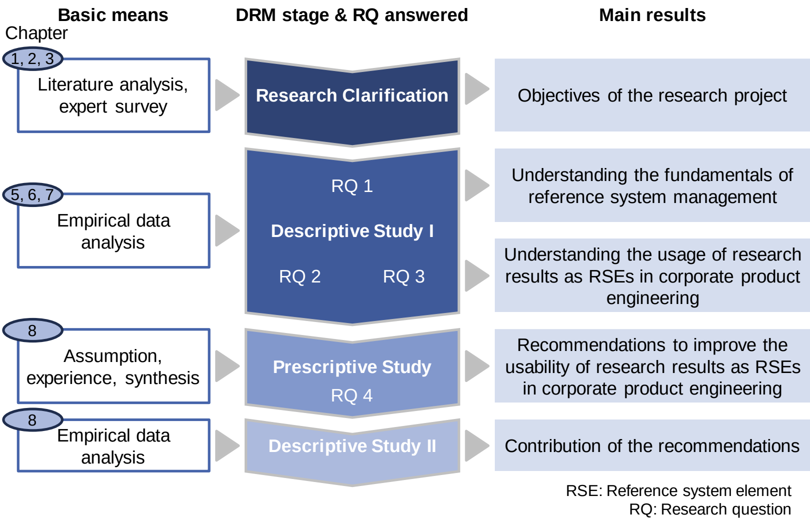


Figure 4.1: Research stages of the DRM framework, including the corresponding research questions, chapters of this thesis, used research methods, and main results. Adapted from Blessing and Chakrabarti (2009).

Based on the results of the Descriptive Study I, Chapter 8 covers the *Prescriptive Study* of this thesis. It provides recommendations to overcome the challenges and barriers identified. Thus, it provides recommendations for corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers to improve the usability of research results as reference system elements in corporate product engineering.

Chapter 8 also comprises the *Descriptive Study II* of this thesis. The study design ensures an initial evaluation of the recommendations.

Depending on the research project, researchers can put different foci on the DRM's four stages. Here, researchers do not follow the four stages sequentially but in parallel and iteratively from the beginning. As shown in Figure 4.2, Blessing and Chakrabarti (2009) distinguish between seven types of research projects in which researchers can conduct the stages using review-based, comprehensive, or initial studies. A comprehensive study adds the results of studies conducted by the researcher to literature-based findings. An initial study does not finish a stage comprehensively but closes a research project. It demonstrates the consequences of the findings and prepares them for further research.

Type	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1	Review-based →	Comprehensive		
2	Review-based →	Comprehensive →	Initial	
3	Review-based →	Review-based →	Comprehensive →	Initial
4	Review-based →	Review-based →	Review-based → Initial/ Comprehensive ←	Comprehensive
5	**Review-based →**	**Comprehensive →**	**Comprehensive →**	**Initial**
6	Review-based →	Review-based →	Comprehensive →	Comprehensive
7	Review-based →	Comprehensive →	Comprehensive →	Comprehensive

Figure 4.2: Design research project types and positioning of this thesis. Adapted from Blessing and Chakrabarti (2009).

This thesis follows the DRM type five, which is a combination of types two and three. Type two thoroughly analyzes the existing situation, followed by an initial Prescriptive Study. An initial Prescriptive Study outlines the potential of the findings to improve product engineering. It defines factors of high impact on success and outlines how to address these factors. Type three focuses on the prescriptive study and adds an initial Descriptive Study II to evaluate the developed support. (Blessing & Chakrabarti, 2009) Here, this thesis focuses on the aspects of type two (comprehensive Descriptive Study I and initial Prescriptive Study), as this thesis concludes with the derivation of recommendations to improve the usability of research results as reference system elements in corporate product engineering. To evaluate the recommendations initially, type three adds an initial Descriptive Study II.

4.2 Overview of the Used Research Methods and Research Environment

This thesis used different research methods in different research environments at different stages to achieve the research objective and answer the research questions. The studies of this thesis also combine several research methods within individual stages. Figure 4.3 provides an overview of the research methods used in this thesis.

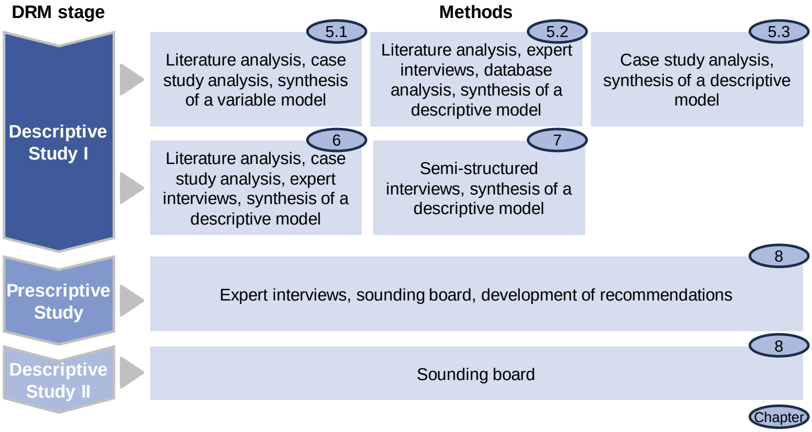


Figure 4.3: Overview of the research methods used in this thesis within the different stages and their allocation to the chapters and research stages of this thesis.

The respective chapters (Chapters 5 to 8) describe the different research methods. These chapters explain the selection and detailed execution of the methods and discuss the study designs, including the limitations. Blessing and Chakrabarti (2009) provide a detailed overview of research methods. Here, they offer the question-method matrix to select fitting research methods to answer the research questions. This matrix focuses on assessing the achievable quality of the results and the necessary effort for both the researcher and other people involved (e.g., study participants). Based on the DRM and iPeM's structure (cf. Subsection 2.2.2), Marxen (2014) provides a more specialized framework to support researchers researching and developing design-support methods. This framework also includes established methods from other disciplines that can be used in engineering methodology practice.

As the primary research environment, this thesis used the IRTG 2078. As previously stated, this thesis is part of the IRTG 2078: “Integrated engineering of continuous-discontinuous long fiber reinforced polymer [(CoDiCoFRP)] structures” of the German Research Foundation (DFG)[1]. The main research goal of this IRTG is “to develop robust integrated engineering strategies for materials design as well as for structure and process optimization of CoDiCoFRP” (Böhlke et al., 2018, p. 5)[2]. Figure 4.4 shows the IRTG’s structure.

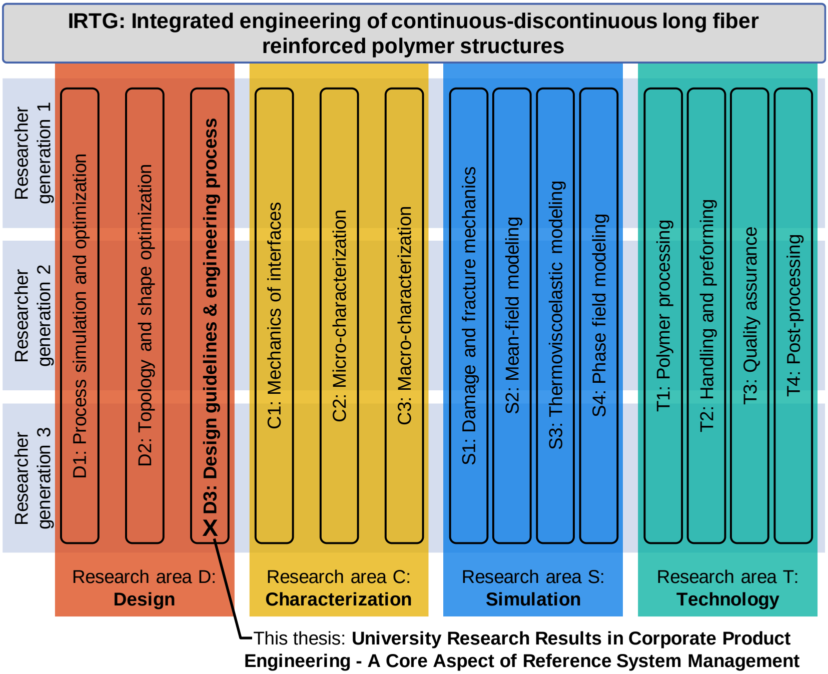


Figure 4.4: Structure of the research environment IRTG 2078 “Integrated engineering of continuous-discontinuous long fiber reinforced polymer [(CoDiCoFRP)] structures”.

For nine years, three generations of doctoral researchers studied different aspects of integrated engineering of continuous-discontinuous long fiber reinforced polymer

[1] GRK 2078
[2] Approved research proposal (unpublished)

(CoDiCoFRP) structures. Therefore, the IRTG organizes 14 parallel research projects in four research areas: Design (D), Characterization (C), Simulation (S), and Technology (T). This thesis results from the research project “D3: Design guidelines and engineering process” and was prepared in research area Design in the third generation. Within the IRTG framework, the task of the three D3 projects was to support corporate engineers in the engineering of CoDiCoFRP structures and to support the transfer of the IRTG’s results into corporate engineering. While D3’s first and second generation researched “situation-specific design guidelines” for “product development with fiber-reinforced plastics” (Butenko, 2020) and the “[m]odelling and [m]easuring [of] the [s]ystem of [o]bjectives [m]aturity [l]evel” (Richter, 2023), the thesis at hand is the bracket around all the IRTG’s results. As deduced in Chapter 3, it researched and developed the field of research results as possible usable reference system elements for corporate product engineering as one core aspect of RSM – Reference System Management to support the transfer of the IRTG’s results into corporate product engineering. Therefore, this thesis analyzed the work of other doctoral researchers and relied on the Industry Advisory Board.

Additionally, this thesis used the Advanced Systems Engineering (ASE) initiative of the German Federal Ministry of Education and Research (BMBF)[3] to complement the research environment IRTG, which focused on basic research. In the ASE initiative, the BMBF funded ten application-oriented research projects of research-industry consortia and one accompanying scientific project (AdWiSE[4]). While the ten collaborative research projects researched and developed new methods and tools for Advanced Systems Engineering (cf. Subsection 2.2.4), the AdWiSE project scientifically accompanied these projects. Being part of the AdWiSE team, the ASE initiative and its collaborative research projects offered a perfect research environment in which to research the usage of research results in corporate product engineering.

[3] “Handling the complexity of sociotechnical systems – a report on Advanced Systems Engineering for the value creation of tomorrow (PDA_ASE)” of the research program: “Innovations for Tomorrow’s Production, Services, and Work”.
[4] https://www.advanced-systems-engineering.de/

5 Fundamentals of Reference System Management

Apriori, this chapter introduces RSM – Reference System Management as a core aspect of product engineering through three preliminary studies as the first part of the Descriptive Study I (cf. Chapter 4). As explained in Section 3.1, RSM describes the initial and continuous synthesis and analysis of the reference system[1]. Thus, RSM organizes the interaction of the engineering team with the reference system. The goal of reference system management activities is to efficiently provide a well-suited reference system as the basis and starting point for developing a new system generation. Thus, addressing the superordinate research goal of this thesis as deduced in Section 3.1, this chapter explains the reference system's general fundamentals. Therefore, this chapter answers the following research question (cf. Section 3.4):

RQ1. What are the fundamentals of the reference system within the model of SGE – System Generation Engineering?

The following three sub-research questions break down research question one to further operationalize it:

- RQ1.1 Which factors from the context of product engineering influence the reference system and its elements?
- RQ1.2 From which sources can reference system elements originate, and how can they be acquired?
- RQ1.3 How can the reference system elements be structured within the reference system?

As illustrated in Figure 5.1, Section 5.1 first analyzes the influences of the context of an engineering project on the reference system and its elements, answering RQ1.1. Therefore, it also explains the reference system's characteristics and elements. Second, Section 5.2 demonstrates the diversity of possible reference system elements by systematically explaining their sources, answering RQ1.2.

[1] As introduced in Section 2.3.1, the reference system, mathematically, is a collection of multiple reference system elements, not a specific, single artifact.

Furthermore, it introduces methods and tools to identify and acquire reference system elements from different sources. Lastly, Section 5.3 describes the reference system's internal structure to systematically model the reference system elements within the reference system, answering RQ1.3.

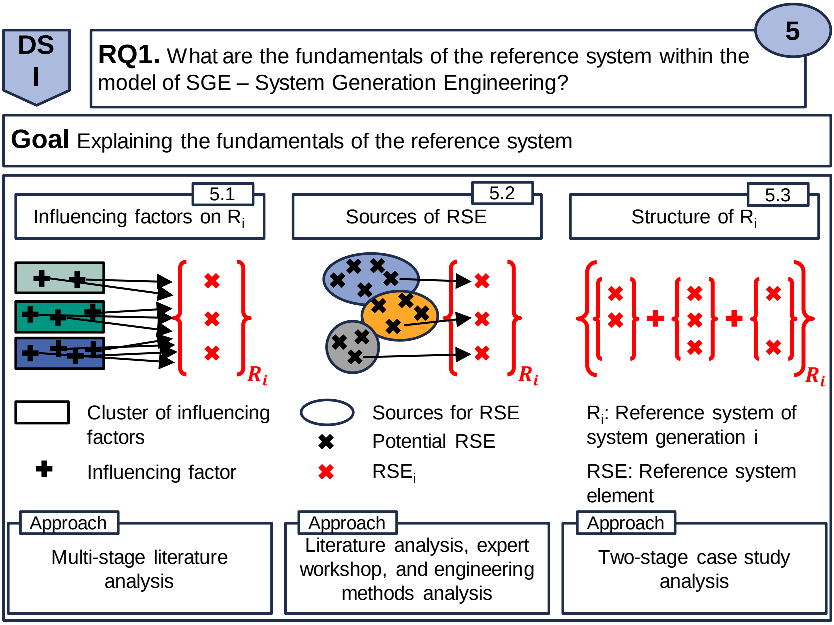


Figure 5.1: Overview of Chapter 5: The respective sections develop the fundamentals of RSM – Reference System Management to answer the first research question.

5.1 Factors Influencing the Reference System and its Elements

As the analysis of the state of research shows (cf. Section 2.3), the reuse of reference system elements for the design of new system generations is well accepted. These studies and models focus on the relations of reference system elements and (sub-)systems of the new system generation or design support based on these relations. However, the available literature neglects the design and composition of the reference system. Studies that examine the context and surroundings of the engineering project for impacts on the reference system are missing (cf. Section 2.2). Product engineering consists of complex activities that are subject to a dynamic context (Blessing & Chakrabarti, 2009). To fill this gap, the following study aims to identify the factors influencing the reference system. At the same time, the study identifies characteristics of the reference system and its elements, which these factors influence. Thus, this section answers the following sub-research question:

> RQ1.1 Which factors from the context of product engineering influence the reference system and its elements?

Figure 5.2 illustrates the goals and approach to identify and analyze factors from the context and surroundings of product engineering projects influencing the reference system.

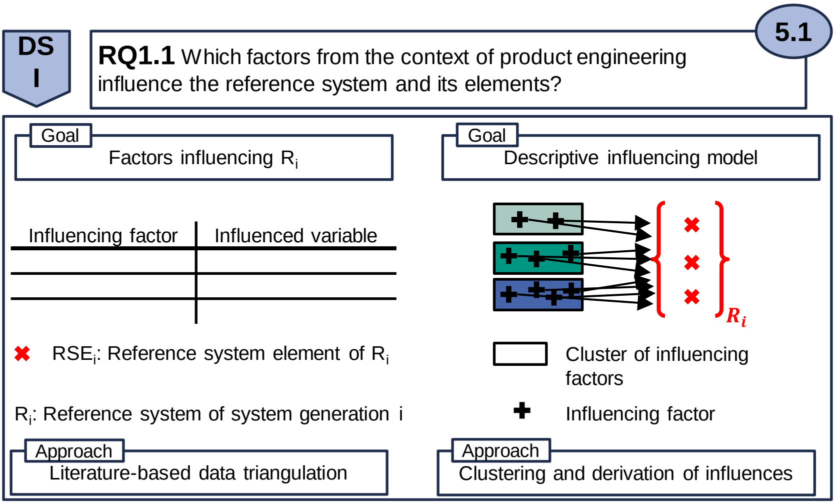


Figure 5.2: Goals and approach to analyze the context and surrounding of product engineering projects for factors influencing the reference system.

Factors from the context and surroundings of engineering projects influence the entire reference system or its elements, or single characteristics of the reference system or its elements. This study builds on a literature-based data triangulation[2] to research these factors and their impact. It produces an interrelation model of influencing factors and characteristics of the reference system as a summary of the results.

The results of this study were published at a scientific conference as specified (Kempf, Sanke, et al., 2022). They were the subject of a student thesis that the author of this thesis co-supervised (Sanke, 2021)[3].

5.1.1 Research Approach

The literature analysis consisted of a triangulation combining the analysis of knowledge and design reuse literature, case studies, and process models of product engineering. Figure 5.3 depicts the research approach of the study.

[2] A triangulation combines multiple research methods or analyzes different data sources to approach an issue from different perspectives and to reduce errors and biases. This approach helps increase the validity of findings. Blessing and Chakrabarti (2009) based on Denzin (2017) which was originally published in 1970.
[3] Student thesis (unpublished)

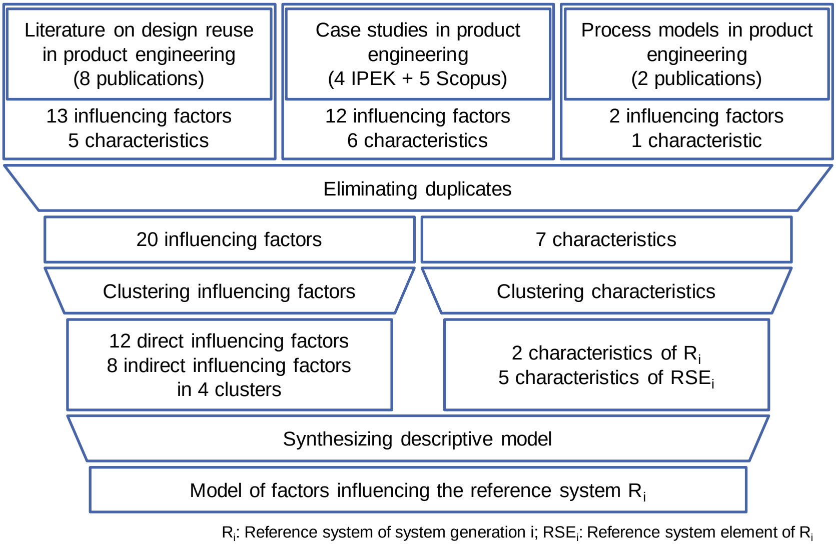


Figure 5.3: Approach to identify and analyze influencing factors and characteristics of the reference system and its elements.

First, the study followed a backward reference-searching approach to analyze relevant literature on knowledge and design reuse. Based on the publication introducing the reference system of the model of SGE (Albers, Rapp, et al., 2019), the study traced back the referenced publications. It analyzed eight publications for factors influencing the entire reference system, its elements, or single characteristics. The study identified 22 relations of 13 influencing factors, with five characteristics of the reference system and its elements.

In the second step, the study analyzed nine case study publications describing product engineering projects for factors influencing the entire reference system, its elements, or single characteristics. Four of these nine case studies were from IPEK in the context of system generation engineering. The remaining five case studies resulted from a systematic literature review in the scientific database Scopus using the search terms shown in Table 5.1.

Table 5.1: Search terms and database used to identify case studies. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[4].

Product engineering	Case study	Reuse
Product development	Case study	Knowledge reuse
Product engineering		Design reuse

The study identified 22 relations among 12 influencing factors and six characteristics of the reference system and its elements.

During the third step, the study analyzed process models of product engineering to identify factors that influence the entire reference system, its elements, or single characteristics. The study identified two relations between two influencing factors, with one characteristic of reference system elements.

In summary, the study identified twenty different influencing factors that affect two characteristics of the entire reference system and five characteristics of reference system elements. The study divided the twenty influencing factors into twelve direct and eight indirect factors. Indirect factors affect other influencing factors, while direct factors affect the characteristics of the reference system or its elements. Finally, the study allocated the identified influencing factors to the four clusters: *team/ people, system, organization, and (macro-)economy,* based on the seven facets of design: "*people, [process], product, knowledge/ methods/ tools, organization, micro-economy[,] and macro-economy*", according to Blessing and Chakrabarti (2009, p. 5). The study then summarizes the influencing factors and characteristics of the reference system in an interrelation model. (Kempf, Sanke, et al., 2022) and (Sanke, 2021)[5]

The following subsection presents the results of the study.

[4] Student thesis (unpublished)
[5] Student thesis (unpublished)

5.1.2 Factors Influencing the Reference System and its Elements

As Table 5.2 shows, three factors of the cluster *team/ people*, nine factors of the cluster *system*, three factors of the cluster *organization*, and five factors of the cluster *(macro-)economy* influence the reference system and its elements. Appendix B presents a short description of all the influencing factors. These factors influence the two general characteristics of the reference system: *homogeneity* and *terminology*. Besides, the factors influence the five characteristics of reference system elements: *approval for use*, *type*, *origin*, *level of detail*, and *maturity level*. (Kempf, Sanke, et al., 2022) and (Sanke, 2021)[6]

Table 5.2: Distribution of the identified factors influencing the reference system across four clusters based on the seven facets of design (Blessing & Chakrabarti, 2009).

Team/ people	System	Organization	(Macro-)economy
3 factors cf. Table 5.3	9 factors cf. Table 5.4	3 factors cf. Table 5.5	5 factors cf. Table 5.6

The first cluster, team/ people, contains factors related to the human aspects of the engineering project (cf. Table 5.3). All three factors directly influence the characteristics of the entire reference system or its elements.

[6] Student thesis (unpublished)

Table 5.3: Influencing factors on the reference system in the cluster team/ people. **Factors in bold** are direct influencing factors. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[7].

Influencing factor	Influenced characteristic	Source
Experience of engineer	Homogeneity of team	(Pfaff et al., 2021)
	Type of RSE_i**	(Markus, 2001)
	Level of detail of RSE_i**	
Homogeneity of team	Homogeneity of R_i*	(Albers, Rapp, et al., 2019)
		(Sassanelli et al., 2021)
Origin of engineer	Homogeneity of team	(Sassanelli et al., 2021)
	Origin of RSE_i**	(Albers, Bursac, & Rapp, 2017)
	Terminology of R_i*	(Vezzetti et al., 2011)
		(Zhang et al., 2017)

*Characteristic of reference system R_i
**Characteristic of reference system elements RSE_i

Considering, e.g., the factor *experience of engineer* illustrates the individuality of the influences. In the considered case, the low experience of the engineers led to the inclusion of external experts and partners, which led to a heterogeneous team (cf. Pfaff et al., 2021). This case is unique as it considers a start-up. More typically, engineers' experience is one dimension of the homogeneity of the team, as the team can consist of members with similar or diverse experiences. Besides, the engineers' experience can influence the type and level of detail of reference system elements they select. More experienced engineers can use reference system elements with a low level of detail because they can compensate for the lack of information with their experience. With extensive experience, they have a broader base to draw for reference system elements (e.g., more projects they have already participated in). However, the study revealed a lack of research in the field of human factors in the composition of the reference system. While humans form the center of product engineering and need special attention (Albers, 2010), the study only identified three factors related to the humans in the cluster team/ people influencing the reference system. The analyzed literature presents no relation of factors such as the engineers' creativity or the size of the team with the reference system.

The second cluster, system, contains the factors related to the system in development and the respective engineering process (cf. Table 5.4). Here, seven of the nine factors are direct influencing factors, and two are indirect influencing factors.

[7] Student thesis (unpublished)

Table 5.4: Influencing factors on the reference system in the cluster system. **Factors in bold** are direct influencing factors. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[8].

Influencing factor	Influenced characteristic	Source
Activities of product engineering	Type of RSE_i**	(Sivaloganathan & Shahin, 1999)
Development time	Origin of RSE_i**	(Albers, Fahl, et al., 2020)
		(Ettlie & Kubarek, 2008)
Number of cooperating companies	Homogeneity of R_i*	(Wouters & Kerssens-van Drongelen, 2004)
	Homogeneity of team	(Albers, Bursac, & Rapp, 2017)
Number of variants	Structure of the system architecture	(Wyatt et al., 2009)
Origin of RSE**	Type of RSE_i**	(Albers, Rapp, et al., 2019)
System generation	Homogeneity of R_i*	(Pakkanen et al., 2019)
	Level of detail of RSE_i**	(Albers, Rapp, et al., 2019)
		(Wyatt et al., 2009)
	Origin of RSE_i**	(Albers, Rapp, et al., 2019)
		(Pakkanen et al., 2019)
		(Pfaff et al., 2021)
Product lifecycle duration	Origin of RSE_i**	(Albers, Reiss, Bursac, & Richter, 2016)
Production volume	Standardization level of components	(Baxter et al., 2008)
Structure of the system architecture	Origin of RSE_i**	(Wouters & Kerssens-van Drongelen, 2004)
	Standardization level of components	

*Characteristic of reference system R_i
**Characteristic of reference system elements RSE_i

System generation is one example of an influencing factor in the cluster system. A $G_{i=1}$ engineering project can influence the homogeneity of the reference system and the origin of reference system elements. It can use various reference system elements from various sources, as no direct internal predecessor generation is present. However, this is not exclusive to a $G_{i=1}$ engineering project. The other way around, a new system generation with many predecessor generations will have many reference system elements from the previous generations, which are available in a high level of detail. The factor *origin of reference system elements* is unique because this is the only characteristic of reference system elements being an influencing factor simultaneously (influencing the type of reference system elements).

[8] Student thesis (unpublished)

While system is the cluster containing the most influencing factors, the study especially identified an underrepresentation of process-related factors. The *activities of product engineering* influence the reference system. However, the study only identified a relation to the type of reference system elements. Depending on the activity, the reference system will require, e.g., CAD files, requirements, material characteristics, etc. However, the study did not reveal detailed information on the preferred characteristics of the reference system and its elements depending on the engineering activity. Only two process models (cf. (VDI Verein Deutscher Ingenieure e.V., 2019a) and (Albers, Reiss, Bursac, & Richter, 2016)) describe factors influencing the reference system. None of the two identified factors (product lifecycle duration and type of company) are related to the engineering process. This finding leads to the conclusion that the design and the influence of the process on the design of the reference system play a subordinate role in currently established process models.

The analysis of the factors of this cluster demonstrated the relevance of cross-interrelations of the factors, too. For example, the study revealed that a modular structure of the system architecture can encourage the use of internal reference system elements. This relation might be true and beneficial in the case of an established company using a modular design kit. On the other hand, e.g., a start-up might use a modular system architecture to enable the usage of external reference system elements to include these in their designs. Thus, the simple relation that a modular system architecture leads to a reference system with internal reference system elements cannot be made without considering the other factors. Furthermore, in an engineering project developing a new system generation with many predecessor generations, reference system elements with a high level of detail might be available and valuable in engineering activities such as modeling the embodiment but obstructive in creative activities such as detecting profiles or ideas.

The third cluster, organization, contains the factors related to the organization surrounding the engineering project and team (cf. Table 5.5). Here, one of the three factors is a direct influencing factor, and two are indirect influencing factors.

Table 5.5: Influencing factors on the reference system in the cluster organization. **Factors in bold** are direct influencing factors. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[9].

Influencing factor	Influenced characteristic	Source
Product variety	Structure of the system architecture	(Corso et al., 1999)
Standardization level of components	Level of detail of RSE_i**	(Albers, Rapp, et al., 2019)
	Maturity level of RSE_i**	(Wouters & Kerssens-van Drongelen, 2004)
Type of company	Experience of engineer	(Pfaff et al., 2021)
	Number of cooperating companies	
	Number of variants	(VDI Verein Deutscher Ingenieure e.V., 2019a)
	Origin of engineer	(Pfaff et al., 2021)

**Characteristic of reference system elements RSE_i

One example of this cluster is the factor *type of company*. Herby, especially the company's age and size, can influence the experience and origin of the engineers employed. For example, a start-up can have more inexperienced engineers, with a significant number coming directly from universities.

The fourth cluster, (macro-)economy, contains factors related to the organization's surroundings (cf. Table 5.6). Here, one of the five factors is a direct influencing factor, and four are indirect influencing factors.

[9] Student thesis (unpublished)

Table 5.6: Influencing factors on the reference system in the cluster (macro-) economy. **Factors in bold** are direct influencing factors. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[10].

Influencing factor	Influenced characteristic	Source
Corporate partnership	Number of cooperating companies	(Albers, Bursac, & Rapp, 2017)
Industry/ branch	Legal situation	(Hernandez Pardo et al., 2011)
	Market uncertainty	(Alblas & Jayaram, 2015)
	Product lifecycle duration	(Corso et al., 1999)
	Standardization level of components	
	Structure of the system architecture	
		(Pakkanen et al., 2019)
Legal situation	Origin of engineer	(Wyatt et al., 2009)
	Structure of the system architecture	(Wouters & Kerssens-van Drongelen, 2004)
		(Wyatt et al., 2009)
Market uncertainty	Development time	(Alblas & Jayaram, 2015)
	Structure of the system architecture	
		(Wouters & Kerssens-van Drongelen, 2004)
Protection status	Approval for use of RSE_i**	(Albers, Bursac, & Rapp, 2017)
		(Albers, Rapp, et al., 2019)

**Characteristic of reference system elements RSE_i

The *legal situation* is one example of the influencing factors within this cluster. This factor considers the legal surroundings in which the system in development will operate. An insecure/ unstable legal situation can drive a company to apply a modular system architecture to react flexibly to changes in legal regulations. In larger enterprises, an insecure legal situation can lead to specialized thematic experts who will support the core engineering team in certain engineering decisions on demand. Therefore, the legal situation can influence the origin of engineers, too.

The influencing model in Figure 5.4 contains all identified influencing factors and the given relations and influences. The model shows that the influence of the factors of the clusters system and team/ people is more direct than of the clusters (macro-) economy and organizations. These two clusters mainly influence factors of the clusters system and team/ people.

[10] Student thesis (unpublished)

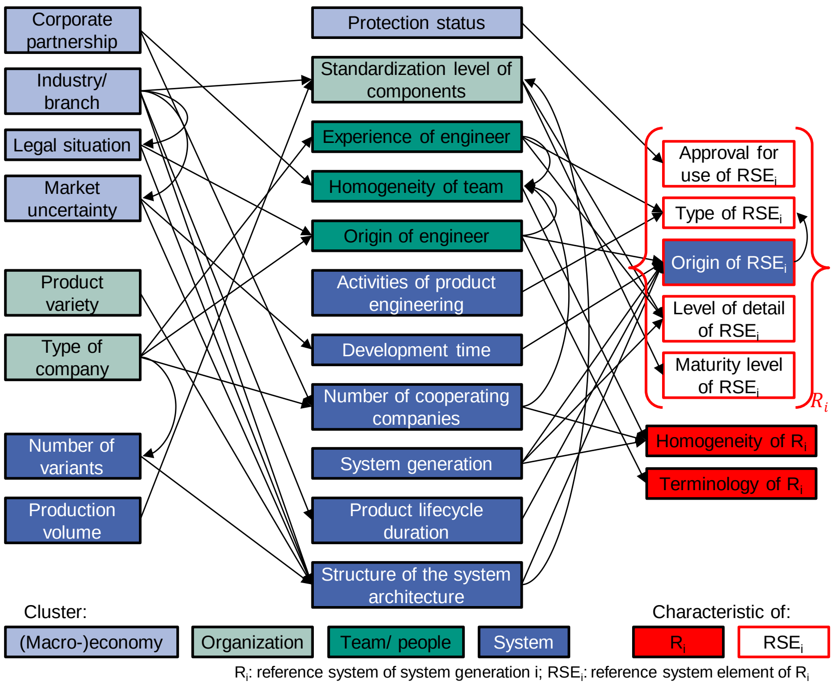


Figure 5.4: Factors influencing the characteristics of the reference system and its elements directly (middle column) and indirectly (left column). Most factors of the clusters (macro-)economy and organization are indirect factors. All factors of the cluster team/ people and most of the cluster system are direct influencing factors. Adapted from Kempf, Sanke, et al. (2022) and Sanke (2021)[11].

Thus, the factors of the clusters system and team/ people are most interesting for the development of the reference system and collection of reference system elements. However, these clusters and their influencing factors cannot be considered isolated; the indirect influencing factors must be considered, too. The influencing model demonstrates again that the reference system's design is a highly complex process. It depends on multiple interconnected influencing factors that can

[11] Student thesis (unpublished)

change during the progress of the engineering project. Therefore, these factors must be considered as a system.

Additionally, this study stresses the need for further research into the factors that influence the reference system and its design. As stated, the analyzed literature does not describe many obvious influencing factors. For example, the engineers' creativity is a core factor influencing multiple characteristics of the reference system and its elements, such as the reference system's homogeneity and the type, origin, level of detail, and maturity level of the reference system elements. Similarly, influencing factors originating in the engineering process (design) are widely neglected in the literature. Different product engineering activities (e.g., detect profiles vs. model principle solution and embodiment) and the progress within the engineering process demand different types, origins, levels of details, and maturity levels of reference system elements. The concrete demands of different expressions of these influencing factors require in-depth research to enable the development of design support for designing reference systems. No systematic approach is available in the analyzed literature to support the reference system's design.

5.1.3 Interim Conclusion

Based on the literature-based data triangulation, the study identified 20 factors influencing the reference system or its elements. These factors belong to the clusters team/ people, system, organization, and (macro-)economy. The analysis uncovered possible influences of different expressions of the influencing factors on the characteristics of the reference system as a whole or its elements. Figure 5.5 summarizes the results of Section 5.1.

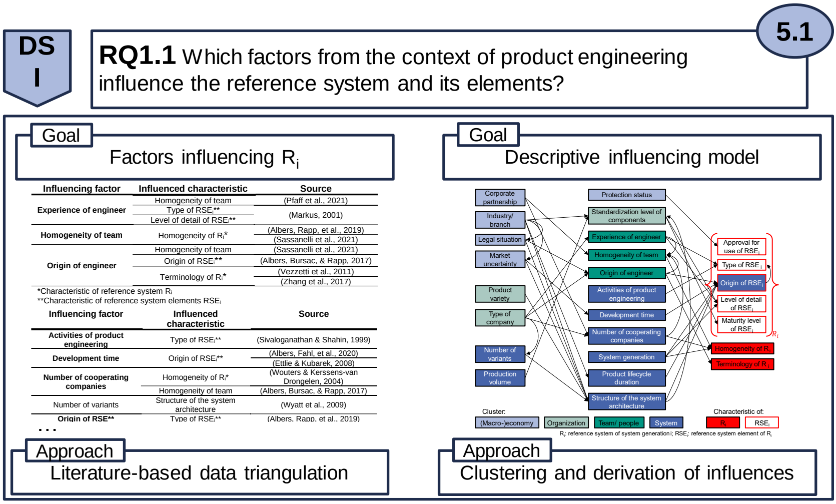


Figure 5.5: Summary of the objectives, approach, and results of the analysis of factors influencing the reference system and its elements. The results are illustrated using icons and presented in detail in Table 5.3, Table 5.4, Table 5.5, Table 5.6, and Figure 5.4.

The clusters system and team/ people are the most important, as they comprise most of the factors directly influencing the reference system and its elements. The clusters organization and (macro-)economy tend to indirectly influence the reference system and its elements via the factors of the first two clusters. Only one factor each, the *standardization level of components* and *protection status*, directly influence the reference system and its elements. To develop design support for designing an individually adopted reference system, the consideration of the direct influencing factors is essential. Here, the design support has to consider all influencing factors, including their interrelations. The factors form a complex system where they influence each other. Different combinations can manifest in different requirements regarding the reference system or its elements (e.g., the modular structure of the system architecture within a company using modular design kits leading to using internal reference system elements vs. enabling the usage of external reference system elements in, e.g., start-ups).

Furthermore, influencing factors can have contradicting implications on the reference system or its elements. A core finding of Section 5.1 is that all influencing factors with their interrelations interact as a complex system. These must be considered when developing design support for the project-specific reference systems' design. Thus, the design of the reference system is a highly complex and creative task. The reference system has to be evolved throughout the whole engineering project as the requirements (e.g., regarding the level of detail of reference system elements) directed on the reference system change with the project's progress, too.

However, the analysis of the influencing factors showed that the literature neglects significant factors such as the engineers' creativity or process-related influences and relations. Especially the relations of engineering activities and according influencing factors on the reference system are highly relevant, as they form the backbone of every engineering process (cf. Ch 2.2.2). These factors are explored insufficiently within the literature. Thus, there is a need for further research to explore and investigate the influencing factors in the different clusters, their interrelationships, and the consequences on the design of an adequate reference system.

The study conducted a literature-based data triangulation following the research approach as presented before (cf. Figure 5.3) to cover different perspectives and a broad range of relevant literature. Thus, the study conducted an approach of backtracking literature on knowledge and design reuse based on the publication of the introduction of the reference system. While this approach enables a focused analysis of the literature on knowledge and design reuse relevant for and leading to the creation and introduction of the reference system by Albers, Rapp, et al. (2019), it neglects literature that these authors did not consider relevant. On the other hand, the study conducted a systematic literature review of case studies to cover the corporate point of view. However, the relatively narrow search string (requiring the combination of "case study" and "knowledge" respectively, "design reuse") and the focus on one database of scientific publications limits this analysis. Since most companies usually do not publish case studies on engineering projects, this analysis only covered cases accompanied by researchers. Thus, these case studies cannot represent the entirety of knowledge and design reuse in corporate product engineering. Finally, to cover the consensus of corporate product engineering and design research, the study analyzed common process models of product engineering.

Since the literature does not widely use the terminology of the reference system of the model of SGE, the study had to interpret the statements in the literature in the context of the reference system. To approach this threat of subjectivity, the author of this thesis extensively discussed the implications with the author of (Sanke, 2021). Thereby, and by the combination of the analysis approaches (triangulation), the study is qualified to answer research question 1.1. as presented in Section 5.1, sufficiently, being a suitable compromise of the trade-offs of the limited resources for the study.

5.2 Methods and Tools to Identify Reference Systems Elements – Development of the RSE Identification Atlas

The literature offers different sources to gather elements for the reference system. However, in the approaches and models for product engineering based on references, no concrete approaches are described to gather reference system elements systematically (cf. Section 2.3). On the other side, various individual methods and tools are available and described in the literature to search for information as input in product engineering. However, these are not connected to the systematic synthesis of the reference system. The following study aims to identify the potential sources of reference system elements and systematically link them with methods and tools to gather the reference system elements to close this gap. Thus, this section answers the following sub-research question:

RQ1.2 From which sources can reference system elements originate, and how can they be acquired?

Figure 5.6 illustrates the goals and approach to identify the potential sources of reference system elements and systematically links them with methods and tools to harvest these sources.

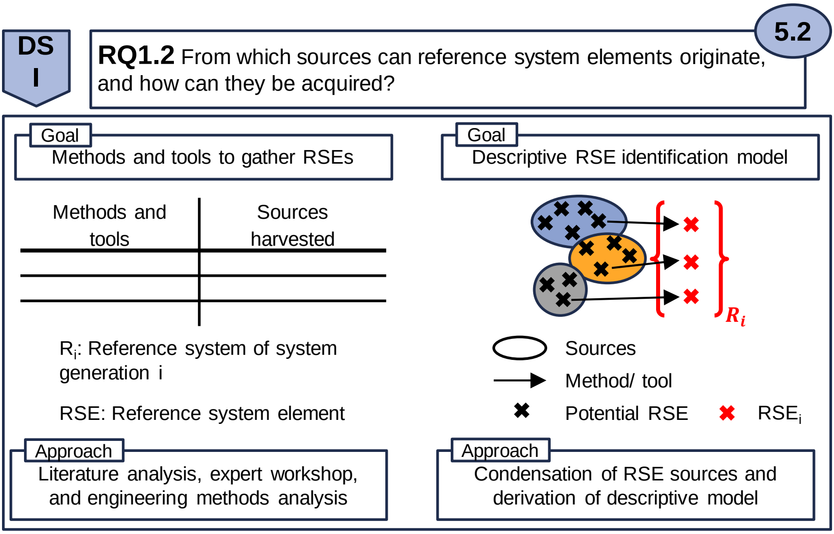


Figure 5.6: Goals and approach to identify potential sources of reference system elements and to systematically link these sources with methods and tools to harvest them.

The study first collects methods and tools that support gathering reference system elements by a literature analysis to answer the research question and address the goals. Here, the study identifies the different sources by analyzing the types of reference system elements that can be gathered using the methods and tools, and their origins. The RSE – Identification Atlas is a descriptive model that condensates the different sources, and methods and tools. The atlas links potential reference system elements from the different sources to the reference system using the methods and tools.

The results of this study were published at a scientific conference and journal as specified (Kempf et al., 2021; Kempf, Rapp, et al., 2023). They were the subject of a student thesis that the author of this thesis co-supervised (Derst, 2021)[12].

[12] Student thesis (unpublished)

5.2.1 Research Approach

As shown in Figure 5.7, the study combined a systematic literature review with an expert workshop and an analysis of a database of engineering methods to identify methods and tools to search for and gather reference system elements.

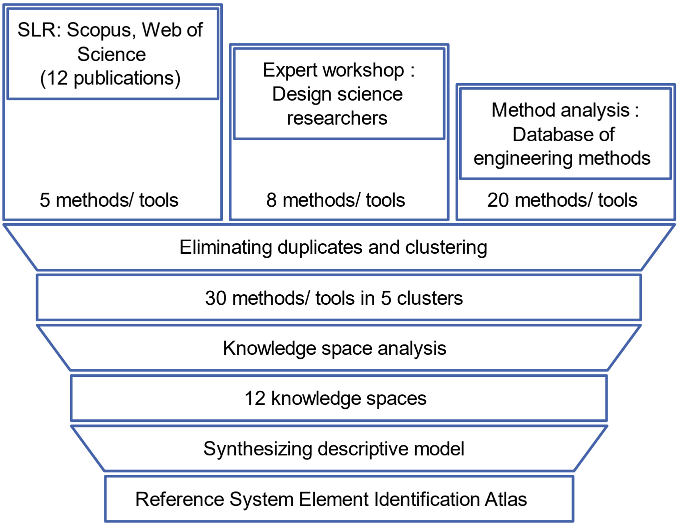


Figure 5.7: Approach to identify and analyze methods and tools to gather reference system elements and to explore the potential sources of reference system elements.

The study started with a systematic literature review in the area of reference-based product engineering to identify methods and tools to search for and gather reference system elements. Therefore, the study used four clusters of search terms to analyze two databases of scientific publications (Scopus and Web of Science), as shown in Table 5.7.

Table 5.7: Used search terms and databases to identify methods and tools. Adapted from Kempf, Rapp, et al. (2023) and Derst (2021)[13].

Product engineering	Method/ tool	References	Search	Database
Product design	Method	Pattern	Identif*	Scopus
Product development	Instrument	Reference	Analysis*	Web of Science
Product engineering	Procedure	Reuse	Bench*	
	Tool	Sample	Scout*	
	Model	Existing product		
	Approach	Existing system		

The study identified 12 relevant publications out of 908 initial results, analyzing them further for methods and tools to search for and gather reference system elements, resulting in 5 methods and tools. In the second step, the study conducted an online workshop with six design science researchers who focused on engineering methods[14] to complement the collection of methods and tools. Third, the study analyzed a database of the KaSPro containing established methods for product engineering activities[15]. In total, the study identified 30 methods and allocated them to five clusters: *creativity methods*, *data analysis methods*, *market/ competition analysis methods*, *similarity methods*, and *trend analysis methods*. Consecutively, the study analyzed the sources that these methods and tools can harvest and identified 12 distinct knowledge spaces that offer potential reference system elements. Finally, the study condenses its findings in designing the Reference System Element Identification Atlas, a descriptive model connecting the different knowledge spaces as sources of

[13] Student thesis (unpublished)
[14] The researchers represent expertise in the fields of creativity and agility in product engineering, collaboration of distributed teams, system generation engineering, and standardization and design kit.
[15] Albers et al. developed and presented the database in Albers, Seiter, et al. (2015) and Reiss et al. (2016).

potential reference system elements to the reference system by the methods and tools. (Kempf, Rapp, et al., 2023) and (Derst, 2021)[16]

The following subsection presents the results of the study.

5.2.2 RSE Identification Atlas

Table 5.8 shows an excerpt of methods and tools, the sources, and potential reference system elements the methods and tools can harvest. Appendix C provides a complete list, briefly describing the methods and tools.

Table 5.8: Excerpt of methods and tools to harvest different sources for reference system elements. Adapted from Kempf, Rapp, et al. (2023) and Derst (2021)[17].

Method/ tool	Source harvested	Exemplary RSE types
Patent analysis	Patent database	Patents
Process mining	Internal/ accessible database	Process (elements)
A2MAC1	A2MAC1 database	Data on competing products, e.g., scans or images
Benchmarking	Competitors/ market	Product data, solution principles
Design catalog	Design catalogs	Construction data
Trend analysis	Competition/ market/ research/ society	Potential future trends

The study allocated the 30 identified methods and tools to five clusters, as illustrated in Table 5.9. The first cluster, *creativity methods*, contains nine methods and tools that spark the creativity of the users by either taking reference system elements from different sources as input (e.g., TRIZ – method or random picture technique) or helping the users to identify possible reference system elements from different sources based on their experience or imagination (e.g., brainstorming). In the second cluster, *data analysis methods*, are five analytical methods and tools that search defined, structured or unstructured, databases (e.g., patent or scientific literature databases) for potential reference system elements. The third cluster, *market/ competition analysis methods*, provides 11 methods and tools that support the users in analyzing the systems and collecting reference system elements of other actors on the market. Head hunting is a special method within this cluster since it also allows one to ac-

[16] Student thesis (unpublished)
[17] Student thesis (unpublished)

quire expertise and implicit information as part of reference system elements. Cluster four, *similarity methods*, collects four methods and tools that help to use reference system elements from various fields by abstracting similarities. The last cluster, *trend analysis methods*, contains one method of analyzing trends to identify potential reference system elements.

Table 5.9: Distribution of the identified methods and tools to harvest different sources for reference system elements to five clusters. Adapted from Kempf, Rapp, et al. (2023).

Creativity methods	**Data analysis methods**	**Market/ competition analysis methods**	**Similarity methods**	**Trend analysis methods**
Brainstorming	Data mining/ KDD	A2MAC1	Analogies	Trend analysis
Delphi method	Design catalogs	Benchmarking	Bionic	
InnoBandit	Literature search	Competitive intelligence	Cluster analysis	
Lateral thinking	Patent analysis	Competitor analysis	Similarity analysis (CBR)	
Method 635	Process mining	Cross industry innovation		
Random picture technique		Head hunting		
Synectic		Joint-venture (co-operation)		
TILMAG		Market analysis/environment analysis		
TRIZ - method		Product reverse engineering		
		Technology portfolio		
		Technology scouting		

This collection offers methods and tools supporting the identification of both process-related (input for the advancement of the operation system) and system/ product-related (input for the advancement of the system of objects and objectives) reference system elements. For example, process mining or competitive intelligence focus on identifying process-oriented reference system elements. Design catalogs or TRIZ, for example, focus on identifying product/ system-oriented solution principles or sub-systems as reference system elements. However, most methods and tools allow the identification of any kind of reference system elements (e.g., in the case of bionic, the walkways of ants are analyzed to optimize traffic organization/ walkways of pedestrians (Fourcassié et al., 2010; Kasture & Nishimura, 2020)).

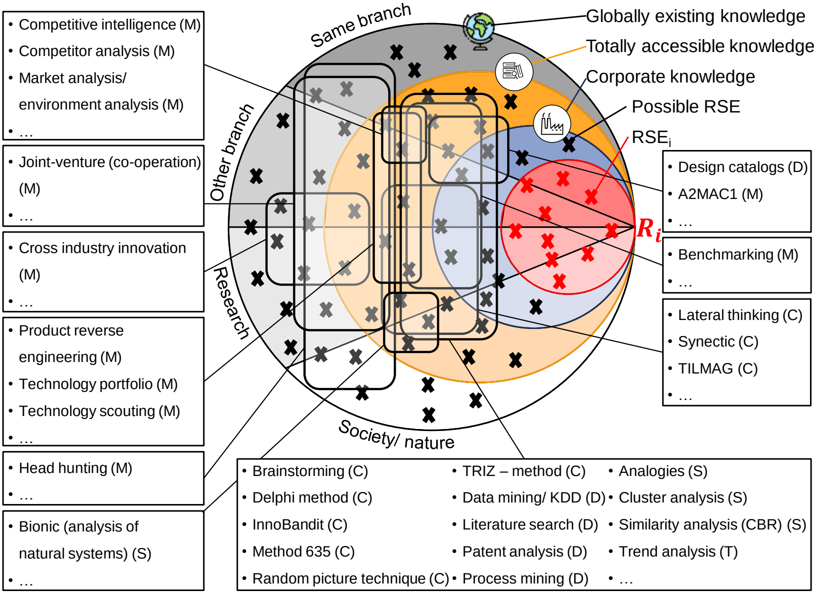
Based on the categorizations from the literature (cf. Subsection 2.3.1), the study distinguishes 12 knowledge spaces, as illustrated in Figure 5.8. The origin and the accessibility of its elements define these knowledge spaces. Potential reference system elements can originate from the same branch, an other branch, research, or society/ nature. These potential reference system elements can already be part of the corporate knowledge (e.g., CAD data of a previous generation), publicly available but not yet part of the corporate knowledge (e.g., competitor products), or globally existing but not accessible by default (e.g., classified military technology, databases behind paywalls).

	Same branch	Other branch	Research	Society/ nature
Corporate knowledge	Potential RSE from the same branch; already part of the corporate knowledge	Potential RSE from other branches; already part of the corporate knowledge	Potential RSE from research; already part of the corporate knowledge	Potential RSE from society/ nature; already part of the corporate knowledge
Totally accessible knowledge - not corporate	Potential RSE from the same branch; accessible but not yet part of corporate knowledge	Potential RSE from other branches; accessible but not yet part of corporate knowledge	Potential RSE from research; accessible but not yet part of corporate knowledge	Potential RSE from society/ nature; accessible but not yet part of corporate knowledge
Globally existing knowledge - not accessible	Potential RSE from the same branch; not accessible	Potential RSE from other branches; not accessible	Potential RSE from research; not accessible	Potential RSE from society/ nature; not accessible

Figure 5.8: Overview of 12 knowledge spaces that contain potential reference system elements.

In general, potential reference system elements already part of the corporate knowledge are easier to access and more detailed than elements of the other two accessibility levels. Getting hold of usually unavailable elements requires extra efforts beyond, e.g., purchasing a competitor's product available on the market.

Condensing the study results and matching the methods and tools with the 12 knowledge spaces, Figure 5.9 presents the Reference System Element Identification Atlas.



(C) Creativity methods, (D) Data analysis methods, (M) Market/ competition analysis methods, (S) Similarity methods, (T) Trend analysis methods R_i: Reference system of system generation i; RSE: Reference system element

Figure 5.9: The Reference System Element Identification Atlas matches the 12 knowledge spaces containing potential reference system elements with 30 methods and tools to draw from these knowledge spaces. The atlas shows 10 clusters of methods and tools that can search different combinations of knowledge spaces. Engineers can use these methods and tools to identify elements for their reference system R_i. Adapted from Kempf, Rapp, et al. (2023).

The atlas shows that engineers can search for and collect reference system elements using specific methods or tools in all 12 knowledge spaces.

5.2.3 Interim Conclusion

Based on the investigations conducted in the study, there are five different types of methods and tools to search for and collect reference system elements from different sources. The five groups that cluster the methods and tools are: creativity methods, data analysis methods, market and competition analysis methods, similarity methods, and trend analysis methods. Engineers and companies[18] can use these methods to search all existing knowledge fields. The study split the globally existing knowledge into 12 searchable knowledge spaces based on the literature and the analysis of the discovered methods and tools. Therefore, it distinguishes the knowledge spaces by origin as: same branch, other branch, research, and society and nature. Following this distinction, the reference system itself consists of elements originating from these fields, too. The accessibility of the potential reference system elements can subdivide these four fields of origin. First, elements can already be part of the corporate knowledge. Second, they can be publicly available but not yet part of the corporate knowledge. Third, they can exist principally but not be accessible due to restraints.

The Reference System Element Identification Atlas combines all these insights. It provides an overview of the 30 identified methods and tools to search for and collect reference system elements. Furthermore, it indicates the different knowledge spaces that the specific methods and tools can harvest. The atlas shows methods and tools that support the search in all four fields of knowledge and methods and tools that focus on only one or two fields. Users must adapt the methods and tools to their specific targets and boundary conditions to search these fields. Figure 5.10 summarizes the results of Section 5.2.

[18] Head hunting, for example, is a method used by the company rather than by an individual engineer.

DS I

5.2

RQ1.2 From which sources can reference system elements originate, and how can they be acquired?

Goal

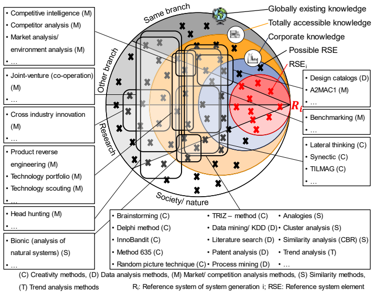
Methods and tools to gather RSEs

Method/ tool	Source harvested	Exemplary RSE types
Patent analysis	Patent database	Patents
Process mining	Internal/ accessible database	Process (elements)
A2MAC1	A2MAC1 database	Data on competing products e. g. scans or images
Benchmarking	Competitors/ market	Product data, solution principles
Design catalog	Design catalogs	Construction data
Trend analysis	Competition/ market/ research/ society	potential future trends

…

Goal

Descriptive RSE identification model



Approach

Literature analysis, expert workshop, and engineering methods analysis

Approach

Condensation of RSE sources and derivation of descriptive model

Figure 5.10: Summary of the objectives, approach, and results of the analysis of possible sources for reference system elements as well as methods and tools to search for and collect reference system elements. The results are illustrated using icons and presented in detail in Table 5.8 and Figure 5.9.

The atlas does not claim to be a conclusive collection of all methods and tools to search for and collect reference system elements. The fact that the study only identified five methods and tools through the systematic literature review does not allow for a holistic claim. Therefore, the study added the expert workshop and the database analysis, leading to 25 additional methods and tools to overcome this shortcoming. Since all these additional methods and tools were described in literature before 2010, the study concluded that methods and tools to identify reference system elements are currently not the research focus. Because of this and the diverse collection of methods and tools, the study decided to stick to the existing search string rather than reformulate it. The study concluded that the low number is due to the year of publication rather than insufficient search terms. This might have caused the systematic literature review to neglect some methods and tools. However, the study anticipates that the consultation of experts and the analysis of a well-established engineering method database compensated for potential shortcomings.

The Reference System Element Identification Atlas represents the first systematic analysis and collection of different engineering and management methods to identify all kinds of reference system elements. Thus, the atlas is an open model. Future research can add further methods and tools to the clusters, add new clusters, or define new search spaces. The study showed that many methods and tools exist that can support identifying reference system elements. However, this connection is rarely made explicit. Fascinating is the implicit use of reference system elements in creativity methods. Usually, reference system elements are not collected explicitly. However, they are used implicitly as input for or to stimulate the creativity and experience of engineers to create new solutions for their engineering tasks directly. This greatly underlines the creative aspect of the creation of the reference system, as postulated by Albers and Düser (2023).

As the relation of the methods and tools to the identification of reference system elements is rarely described explicitly within the methods and tools, implications for the systematic collection of reference system elements could only be drawn rudimentary. All 12 knowledge spaces as sources for potential reference system elements have their specifics and need further research. Here, the Reference System Element Identification Atlas provides a starting point for systematically selecting methods and tools to search for and collect reference system elements and towards a systematic support in synthesizing a reference system. It shows the wide variety of sources and many possibilities for searching for and identifying reference system elements. Therefore, in-depth research is necessary for all fields of knowledge to provide targeted support. However, the simultaneous study of all possible sources appears too extensive for a single dissertation.

5.3 Reference System and the System Triple – Structuring the Reference System

The literature describes the reference system as a collection of elements from existing sociotechnical systems that form the basis for an engineering team to develop a new system generation. Furthermore, it identifies different sources that offer potential reference system elements. (Albers, Rapp, et al., 2019; cf. Sections 2.3 and 2.4). However, the literature does not describe the internal structure of the reference system in further detail. To close this gap, this study aims to better understand the mechanics of the reference system and its relation to the system generation developed on its basis. Therefore, the objectives of this study are to cluster the different types of reference system elements and to define the internal structure of the reference system. Thus, this section answers the following sub-research question:

RQ1.3 How can the reference system elements be structured within the reference system?

Figure 5.11 illustrates the goals and approach to cluster reference system elements and to structure the reference system.

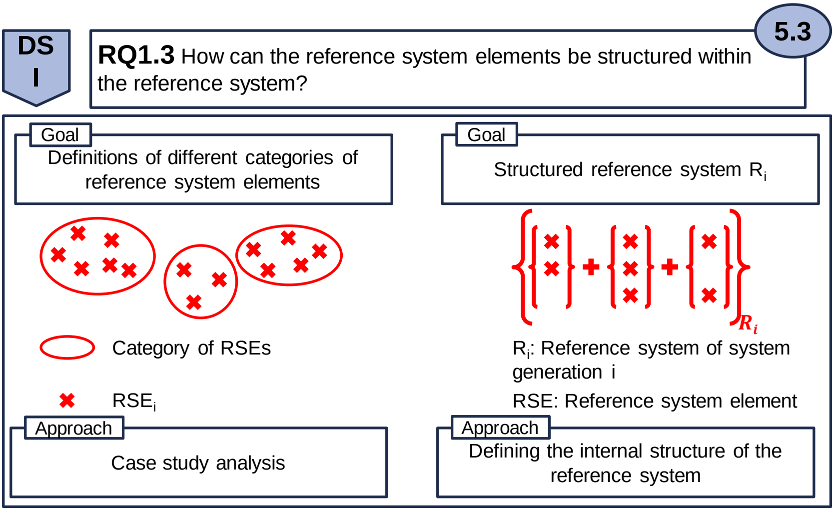


Figure 5.11: Goals and approach to cluster reference system elements and to structure the reference system.

The study analyzes different case studies to identify different categories of reference system elements to answer the research question and address the goals. It analyzes these categories and structures the reference system internally by developing definitions for three subsystems. The study uses the extended system triple of product engineering (cf. Subsection 2.2.1) as the basis to develop these definitions. The results of this study are highly relevant for Advanced Engineering, as structuring the reference system enables to model it consistently, e.g., using model-based system engineering.

The results of this study were published in a scientific journal as specified (Albers, Kempf, et al., 2024).

5.3.1 Research Approach

As shown in Figure 5.12, the study to answer research question 1.3 followed a research approach based on the Design Research Methodology of Blessing and Chakrabarti (2009).

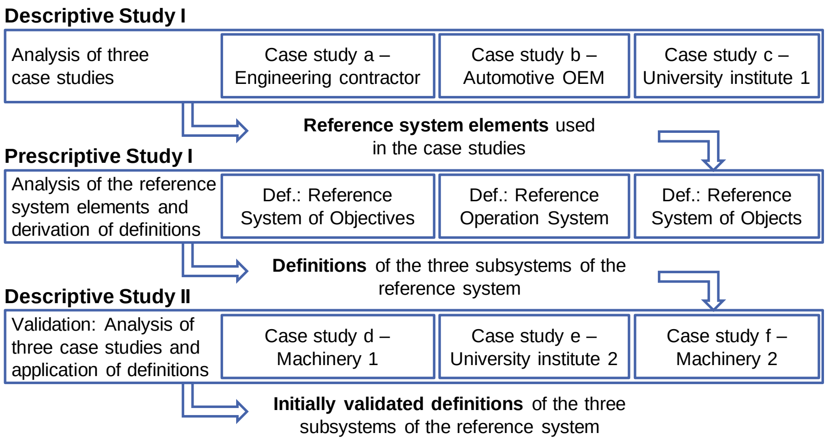


Figure 5.12: Approach to identify and cluster the different types of reference system elements and to define the internal structure of the reference system. Adapted from Albers, Kempf, et al. (2024).

In the first step, based on the Descriptive Study I according to Blessing and Chakrabarti (2009), the study conducted three case studies to gain detailed insights into their use of reference system elements (cf. Table 5.10 Case studies a, b, and c). These case studies discuss different engineering projects and collect the reference system elements used to develop the respective system generation. The study clustered all identified reference system elements into three categories depending on what was developed based on the elements. In the second step, based on the Prescriptive Study according to Blessing and Chakrabarti (2009), the study developed definitions for the three categories of reference system elements forming three subsystems of the reference system – first, the *Reference System of Objectives*, second, the *Reference Operation System*, and third, the *Reference System of Objects*. The study based these definitions on the extended system triple of product engineering (cf. Subsection 2.2.1). In the third step, based on the Descriptive Study II according to Blessing and Chakrabarti (2009), the study used three further case studies of engineering projects to apply and initially evaluate the developed definitions retrospectively (cf. Table 5.10 Case studies d, e, and f). In the study, the researchers had direct access to all six case studies, either participating in or observing the engineering projects.

Table 5.10: Case studies of six different engineering projects. The study used case studies a, b, and c as the basis to develop definitions of three subsystems of the reference system. The study used case studies d, e, and f to evaluate these definitions initially. Adapted from Albers, Kempf, et al. (2024).

Case study	Short description	DRM Stage
a: Engineering Contractor	Development of a light source for a customer as an engineering contractor	DS I
b: Automotive OEM	Requirements management and development of the system of objectives of a new product generation at an automotive OEM	DS I
c: University Institute 1	Development of a test environment using MBSE for knowledge reuse at a university research institute	DS I
d: Machinery OEM 1	Development of a picking robot in an innovation project with a machinery OEM	DS II
e: University Institute 2	Development of a computational optimization method for ribbed long fiber reinforced thermoplast structures	DS II
f: Machinery OEM 2	Development of an automation solution for sheet metal handling	DS II

The following subsection presents the results of the study.

5.3.2 The System Triple Within the Reference System

Table 5.11 shows an excerpt of the reference system elements used in case studies a, b, and c to develop the next system generation. The table clusters the elements into three categories according to their use in the following system generation's development. The analysis showed that engineers use reference system elements in three ways: as input to develop G_i's system of objectives, as input to develop G_i's operation system, and as input to develop G_i's system of objects. Appendix D provides a complete list of all reference system elements used in all case studies that the study identified.

Table 5.11: Excerpt of the reference system elements used in the case studies a, b, and c sorted into three categories according to their use in G_i's development. Adapted from Albers, Kempf, et al. (2024).

Elements used to develop the system of objectives of G_i	**Elements used to develop the operation system of G_i**	**Elements used to develop the system of objects of G_i**
$RSE_{i=n}^{a,1}$: Customer requirements documented in the engineering mandate	$RSE_{i=n}^{a,9}$: Creativity methods	$RSE_{i=n}^{a,2}$: Physical product of the previous system generation
$RSE_{i=n}^{a,5}$: Calculation documentation of the previous system generation	$RSE_{i=n}^{a,13}$: Internal development process	$RSE_{i=n}^{a,3}$: CAD model of the previous system generation
$RSE_{i=n}^{a,8}$: Requirements derived from the previous system generation's wiki documentation	$RSE_{i=n}^{a,14}$: Internal dimensioning (calculation and simulation) guidelines	$RSE_{i=n}^{a,11}$: Prototypes of the system generation in development
$RSE_{i=n}^{a,17}$: Requirements for light sources described in standards and guidelines	$RSE_{i=n+1}^{b,4}$: Standard formulation process for requirement formulation derived from the previous system generation's requirements	$RSE_{i=n}^{a,19}$: Physical interfaces described in standards and guidelines
$RSE_{i=n+1}^{b,3}$: Standard format for requirement formulation derived from the previous system generation's requirements	$RSE_{i=n+1}^{b,10}$: Method descriptions (e.g., guidelines or training documents) of requirements management activities	$RSE_{i=n+1}^{b,1}$: Requirements of the previous system generation
$RSE_{i=n}^{c,6}$: Validation objective of the previous system generation	$RSE_{i=n+1}^{b,11}$: Expert knowledge and experience in the specification process	$RSE_{i=n+1}^{b,5}$: Reconstructed requirements of competitor vehicles
$RSE_{i=n}^{c,7}$: Specified test cases of the previous system generation	$RSE_{i=n}^{c,16}$: Expert knowledge and experience in measurements of virtual torsion compensation	$RSE_{i=n+1}^{b,8}$: Chapter structure of the previous system generation's requirements specification
$RSE_{i=n}^{c,12}$: Requirements based on expert knowledge and experience of influences from the test environment setup on the test variables		$RSE_{i=n}^{c,2}$: Description of the previous generation's (sub-)systems interfaces
		$RSE_{i=n}^{c,8}$: Principle sketch of the previous system generation
		$RSE_{i=n}^{c,18}$: Expert knowledge and experience on (dis-)advantages of different actuation principles

G_i: System generation i; RSE_i: Reference system element

While analyzing the identified reference system elements, the study discovered that the characteristics of these elements depend on the point of view and the goal of the specific project/ respective product engineers. The system triple of product engineering is a model as defined by Stachowiak (1973). The model and its manifestation depend on the perspective of the modelers and addressees and the model's purpose. Thus, the study followed the perspective of the specific project to cluster the reference system elements. This was especially important when clustering the reference system elements of case study b. As Figure 5.13 shows, the case study b's development project under consideration is the development of the after-next-vehicle generation's system of objectives ($G_{i=n+1}^{Vehicle,Requirements\ Spec.}$). This project is a subproject of the after-next-vehicle generation's overall development ($G_{i=n+1}^{Vehicle}$). In this sense, the development project of case study b results in the requirements specification as its system of objects ($G_{i=n+1}^{Vehicle,Requirements\ Spec.}$) which forms the system of objectives of the overall vehicle development project ($G_{i=n+1}^{Vehicle}$). Thus, case study b uses the reference system element $\mathrm{RSE}_{i=n+1}^{b,1}$: *Requirements of the previous system generation* as input to develop its system of objects in the view of case study b's engineering project[19]. However, $RSE_{i=n+1}^{b,1}$ originates from the previous overall vehicle generation's ($G_{i=n-1}^{Vehicle}$) system of objectives and forms the overall vehicle generation in development's ($G_{i=n+1}^{Vehicle}$) system of objectives from a superordinate point of view.

[19] The engineering project considered in case study b used elements of the previous generation ($G_{i=n-1}$) to develop the requirements (system of objectives) of the after-next generation ($G_{i=n+1}$). This is a typical relation within automotive engineering as multiple system generations are developed parallelly. Case study b considers the early phase of the engineering project ($G_{i=n+1}$).

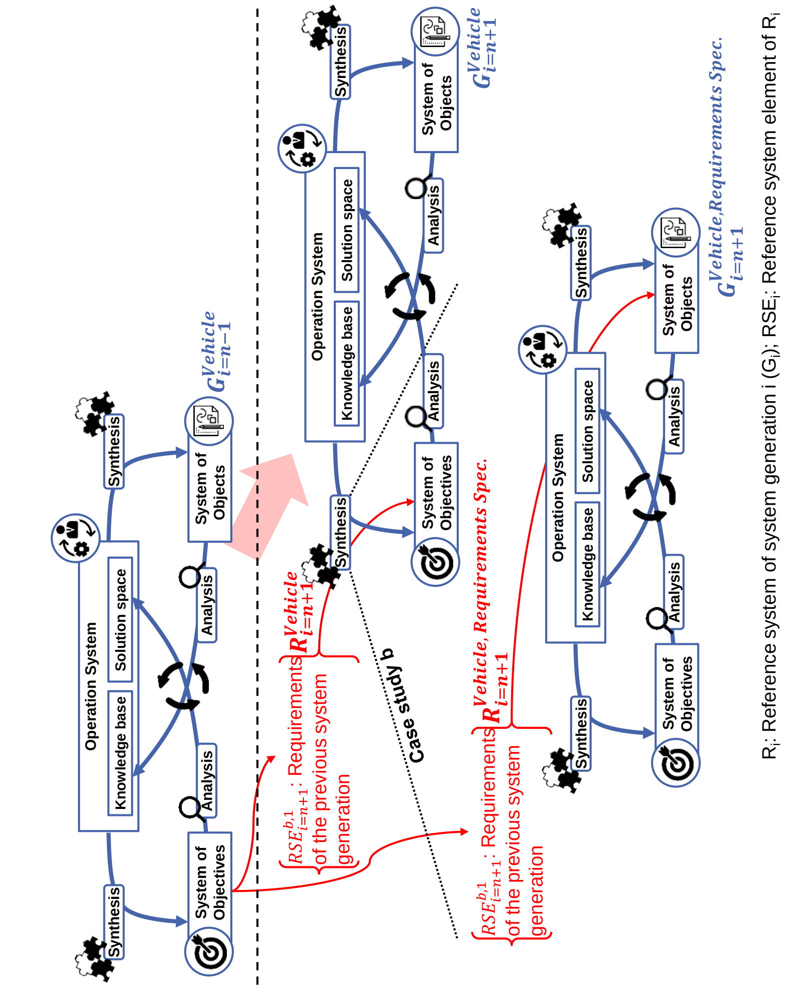


Figure 5.13: View-specific allocation of RSEs: In a case study b-specific point of view, $RSE_{i=n+1}^{b,1}$ originates from the overall previous vehicle generation's system of objectives and serves as input to develop the case study b's system of objects ($G_{i=n+1}^{Vehicle,Requirements\ Spec.}$). From a superordinate point of view, $RSE_{i=n+1}^{b,1}$ serves as input to develop the after-next overall vehicle generation's ($G_{i=n+1}^{Vehicle}$) system of objectives. Adapted from Albers, Kempf, et al. (2024).

These findings lead to the conclusion that using a reference system element depends on the view and goal of the specific engineering project.

Engineers cannot carry over all reference system elements directly. They have to reconstruct or derive elements such as $\mathrm{RSE}_{i=n+1}^{b,5}$*: Reconstructed requirements of competitor vehicles* from other elements, which are reference system elements themselves (e.g., competitor vehicles). This finding also illustrates the relations within the reference system between its elements.

The study used this analysis to develop the following definitions for three subsystems of the reference system: the *Reference System of Objectives*, the *Reference Operation System*, and the *Reference System of Objects*.

Definition 4: Reference System of Objectives

> "The *reference system of objectives* is a subsystem of the reference system R_i containing elements of the *character of the system of objectives' elements*. It is the *basis and starting point for the development of the system of objectives* of the new [system] generation G_i.
> The elements of the reference system of objectives are
> - carried over from existing or planned socio-technical systems and the associated documentation *directly*
>
> or
> - *reconstructed* (via the operation system of G_i) from the reference operation system's elements or reference system of objects' elements."
>
> (Albers, Kempf, et al., 2024, p. 19)

Definition 5: Reference Operation System

> "The *reference operation system* is a subsystem of the reference system R_i containing elements of the *character of the operation system's elements*. It is the *basis and starting point for the planning and definition of the operation system* of the new [system] generation G_i.
> The elements of the reference operation systems are
> - carried over from existing or planned socio-technical systems and the associated documentation *directly*
>
> or
> - *reconstructed* (via the operation system of G_i) from the reference system of objectives' elements or reference system of objects' elements."
>
> (Albers, Kempf, et al., 2024, p. 20)

Definition 6: Reference System of Objects

"The *reference system of objects* is a subsystem of the reference system R_i containing elements of the *character of the system of objects' elements*. It is the *basis and starting point for the development of the system of objects* of the new [system] generation G_i.
The elements of the reference system of objects are

- carried over from existing or planned socio-technical systems and the associated documentation *directly*

or

- *reconstructed* (via the operation system of G_i) from the reference system of objectives' elements or reference operation system's elements."

(Albers, Kempf, et al., 2024, pp. 20–21)

These definitions are distinct from each other to allow the sharp allocation of reference system elements to precisely one of the reference system's subsystems. This is crucial to allow the computer-aided modeling of the reference system and its integration into cross-generational Advanced Engineering approaches.

Figure 5.14 illustrates the presented definitions of the reference system's three subsystems. The variation operator connects them to G_i via carryover variation, attribute variation, and principle variation through G_i's operation system.

The definitions presented already include the insights of the initial evaluation using case studies d, e, and f (cf. Subsection 5.3.1). This evaluation proved the applicability of the definition as the study could assign all used reference system elements of the case studies to one of the subsystems of the reference system (cf. Appendix D). Here, the study discovered that the specification of the intended reference system elements' use is essential to allow the distinct separation and allocation of reference system elements. For example, the engineers of case study e used the reference system element $\mathrm{RSE}_{\mathrm{i=n}}^{\mathrm{e,2}}$*: Design catalogs* in two different ways. First, they used it to derive requirements for the new method's system of objectives ($RSE_{i=n}^{e,2a}$: Design catalogs (to derive requirements)). Second, they used it to identify and carry over functionalities into the new method. Thus, they integrated it into the new method's system of objects ($RSE_{i=n}^{e,2b}$: Design catalogs (to identify functionalities to be implemented)).

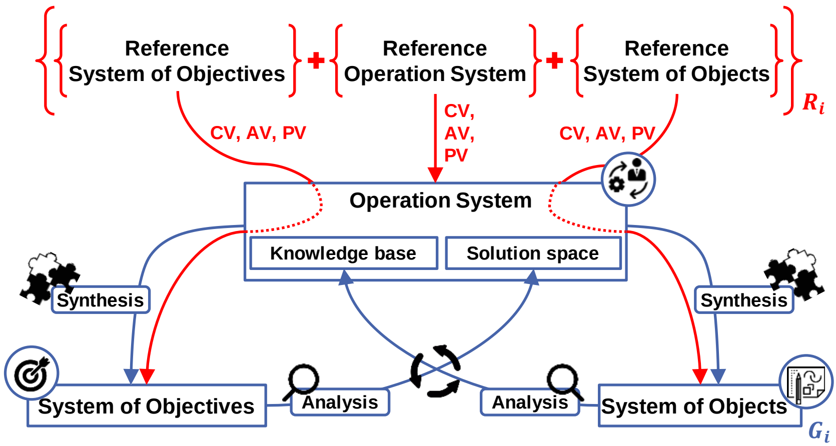


Figure 5.14: The system triple of product engineering defines three subsystems within the reference system R_i. The reference system of objectives is the basis for developing G_i's system of objectives. The reference operation system is the basis for planning and defining G_i's operation system. The reference system of objects is the basis for developing G_i's system of objects. Adapted from Albers, Kempf, et al. (2024).

5.3.3 Interim Conclusion

Just as the development of a new system generation is complex, the synthesis of the according reference system is complex, too. Engineers use reference system elements for all aspects of development projects. They use reference system elements to develop their system of objectives, operation system, and system of objects. At the same time, these elements can be interconnected and interdependent. This study divided the reference system into three subsystems based on the conducted analysis. The reference system of objectives, the reference operation system, and the reference system of objects collect the reference system elements that form the basis for the development of the corresponding subsystem of the system triple of the system generation in development. This study provides distinct definitions for each reference system's subsystem to enable product engineers to allocate their reference system elements to one of the subsystems. Here, the allocation depends on the specific point of view of the respective engineering project. For an engineering team of a subproject of the overall project, reference system elements can be part of a different subsystem of the reference system compared to the overall project, depending on the respective project goals. Suppose engineers use a reference system element as input for multiple subsystems of the system triple of product engineering; in that case, it has to be split up based on its intended use to allow the distinct allocation to the reference system's subsystems. Figure 5.15 summarizes the results of Section 5.3.

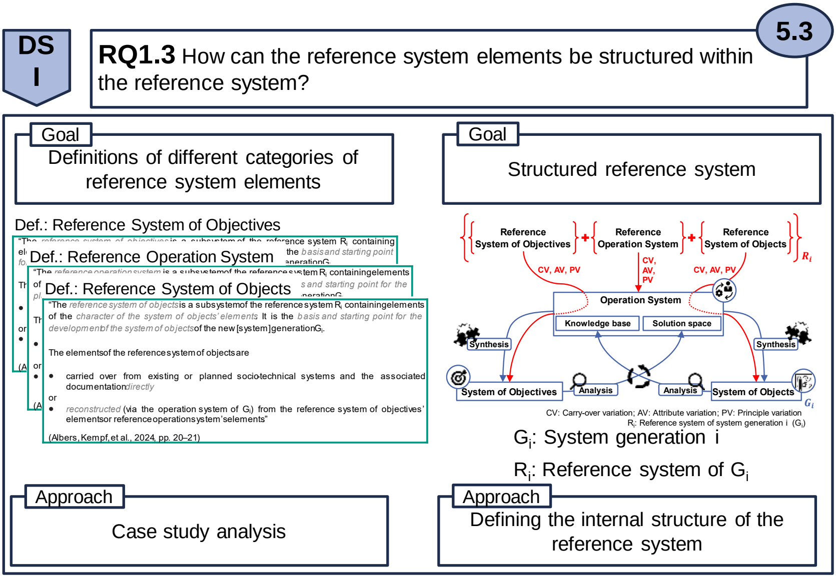


Figure 5.15: Summary of the objectives, approach, and results of the analysis of different categories of reference system elements as well as the definition of three subsystems of the reference system. The results are illustrated using icons and presented in detail in Definition 4 to 6, and Figure 5.14.

The definitions of the reference system's three subsystems allow the distinct allocation of all possible reference system elements used for any engineering activities. This sharp distinction of reference system elements according to their use in the engineering project is vital to support the reference system's synthesis and to include it in cross-generational Advanced Engineering approaches, using model-based approaches in particular. In these Advanced Engineering approaches, the continuous development of multiple parallel and consecutive system generations and the continuous development of the according engineering processes are key to an efficient and effective engineering process. This is only possible with the consequent modeling and consideration of the respective reference system.

As explained in the Research Approach (cf. Subsection 5.3.1), the study initially evaluated the reference system's subsystems by applying their definitions to reference system elements used in three engineering projects (case studies d, e, and f – cf. Appendix D) different from the case studies used to develop the definitions. While this evaluation led to the improvement of the definitions and proved their applicability to various engineering projects in different corporate branches (automotive, different machinery branches, and engineering contractor) and research fields (test bench and design method development), six case studies might appear not to be enough to represent the variety of all engineering projects. However, the explorative study design of using three utterly different case studies to develop the definitions of the reference system's subsystems and successfully applying these definitions to three separate utterly different case studies ensures validity of this study's results. Further, the incorporation of both the system triple of product engineering's and the reference system's definitions highlight the study's definitions of the reference system's subsystems as a valid advancement of earlier research.

However, the theoretical introduction of the reference system's subsystems is just the first step. The development of methodical design support and tooling for the reference system's synthesis and the development of cross-generational Advanced Engineering approaches are major tasks that have not been followed further in this thesis. However, this study provides a solid basis for further research in this field.

5.4 Conclusion

The synthesis of the reference system is a creative and complex task as individual as any system development project. In Chapter 5, this thesis researched and developed the fundamentals of the reference system and Reference System Management to gain a basic understanding of the mechanics of the reference system. Thus, this chapter answered the following research and sub-research questions:

RQ1. What are the fundamentals of the reference system within the model of SGE – System Generation Engineering?

RQ1.1 Which factors from the context of product engineering influence the reference system and its elements?

RQ1.2 From which sources can reference system elements originate, and how can they be acquired?

RQ1.3 How can the reference system elements be structured within the reference system?

This thesis chose a threefold research approach to answer the research questions. Figure 5.16 summarizes the research approach and the core results of Chapter 5.

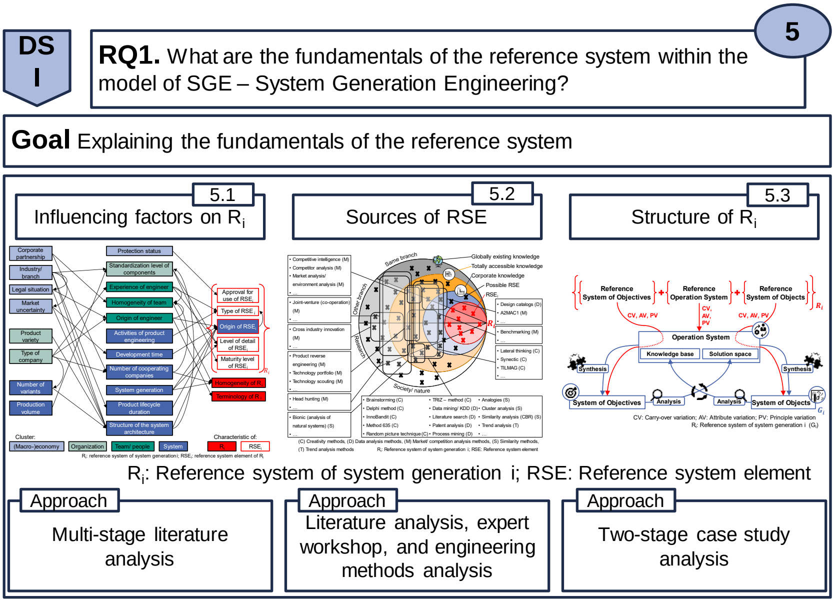


Figure 5.16: Summary of the objectives, approach, and results of the three empirical studies of the first part of the Descriptive Study I to explore the fundamentals of the reference system. The results are illustrated using icons and presented in detail in Figure 5.4, Figure 5.9, and Figure 5.14.

As presented in Section 5.1, the first study identified and discussed 20 factors influencing the reference system and its elements directly and indirectly. These factors are highly interlinked and belong to four clusters. The study shows the complexity of the reference system's environment and, consequently, the complexity of the synthesis of the reference system. The study results provide a basis for researchers to develop design support to assist engineers in the reference system's synthesis. However, the complexity and the engineering project-specific individuality of the influences and their consequences on the reference system hinder the holistic consideration within one dissertation project. A focus on partial aspects is necessary.

As presented in Section 5.2, the second study analyzed the possible sources for reference system elements and connected these with methods and tools to harvest these sources. The study's results form the Reference System Element Identification Atlas connecting 12 knowledge spaces as reference system element sources with 30 methods and tools to search these spaces. Thus, this study initiates the research of systematically collecting reference system elements and developing the reference system systematically. However, since the study could not identify a systematic review in the literature of methods and tools to search for reference system elements, the selection of the 30 methods and tools needs to be considered as initial. Many engineering methods and tools (including, i.a., creativity methods) usually search for or use reference system elements implicitly only. Thus, further in-depth analysis of engineering methods and tools is necessary to complete the Reference System Element Identification Atlas. However, the in-depth consideration of all possible reference system element sources is too grand a task for one dissertation project.

Section 5.3 presents the third study, which analyzed the reference system's structure in detail. This analysis resulted in the definition of three subsystems of the reference system: the Reference System of Objectives, the Reference Operation System, and the Reference System of Objects. These subsystems of the reference system are distinct from each other. Here, the allocation of reference system elements depends on the modeler's and user's intended use and point of view. The reference system's defined subsystems enable the systematic use and integration of the reference system in Advanced Engineering approaches for cross-generational system engineering.

In combination, the results of the first three studies answer the first research question. They explain the mechanics and define the basics of RSM – Reference System Management on a general level and form a solid basis for further research. However, the findings underline the complexity of RSM, too. For example, it became apparent that the combination of concrete influencing factors impacts the search for and selection of reference system elements in different knowledge spaces. However, the connection between the influencing factors, their interplay, and the selection of reference system elements requires further research.

As explained in Section 3.1, this thesis decided to focus on the aspect of reference system elements from research. Of course, this focus hinders the holistic development of RSM. However, research is an excellent starting point for further research as the transfer of research results into corporate engineering is highly relevant to the technological evolution necessary for both economic success and societal benefits (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017). Furthermore, being a highly diverse source for reference system elements due to the variety of research, research is a very eligible focus for this thesis.

6 Development of an Initial Research Results Classification Model

The first step in systematically researching the use of research results as reference system elements in corporate product engineering is understanding the different research result types and their characteristics. A classification model enables further discussions and a common understanding. Thus, this chapter answers the second research question (cf. Section 3.4), being part of the first Descriptive Study (cf. Chapter 4):

RQ2. How can research results be classified to facilitate their exploration as reference system elements in corporate product engineering projects?

The following two sub-research questions break down research question two to further operationalize it:

- RQ2.1. What types of results are generated in research, and what are their characteristics?
- RQ2.2. How can the results from research be sorted in a classification model?

Figure 6.1 illustrates the goals and approach to classify research results to allow their exploration as reference system elements in corporate product engineering projects.

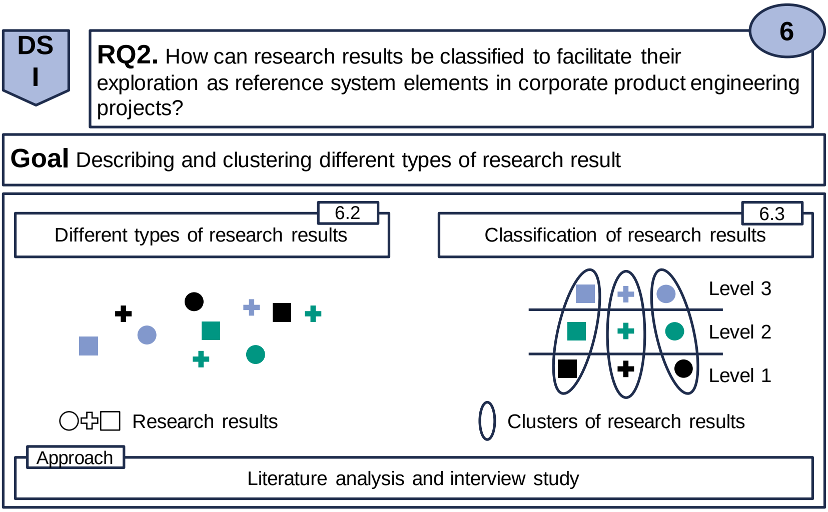


Figure 6.1: Overview of Chapter 6: The respective sections explore different types of research results and their classification to answer the second research question.

The results of this study were published at a scientific conference as specified (Kempf et al., 2024).

6.1 Research Approach

As shown in Figure 6.2, the study combined two systematic literature reviews to analyze the scientific literature for research on different types of research results and their classification. During the process, the study compared and aligned the findings of both reviews.

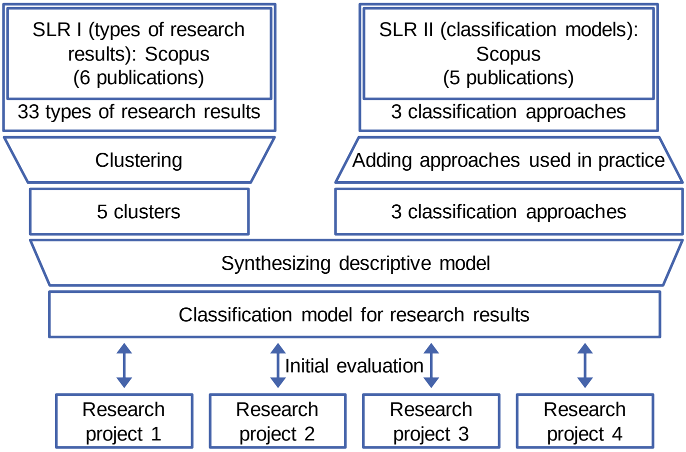


Figure 6.2: Approach to develop a research results classification model based on identifying and analyzing different types of research results and their classification.

The first systematic literature review (SLR I) used the search terms in two clusters, as shown in Table 6.1, to identify and analyze scientific work on different types of research results in one database of scientific publications (Scopus).

Table 6.1: Used search terms and database to identify types of research results. Adapted from Kempf et al. (2024).

Research result	Type	Database
Research* result*	Type*	Scopus
Research* output*	Kind*	
Scien* result*	Form*	
Scien* output*		

Terms such as “result” or “type” are widely used in abstracts of scientific publications. Therefore, the first systematic literature review searched titles and keywords only to increase the share of relevant search results. Starting from 407 publications, the study identified six relevant publications, analyzing them in detail for different types of research results. This analysis resulted in the collection of 33 types of research results. Here, the study identified the five clusters of research result types:

publications, *prototypes*, *equipment*, *data*, and *experience*. Section 6.2 presents the five clusters of research result types.

In the second systematic literature review (SLR II), the study used the search terms shown in Table 6.2 to identify and analyze scientific work on classification approaches in one database of scientific publications (Scopus).

Table 6.2: Used search terms and database to identify approaches to classify research results. Adapted from Kempf et al.Kempf et al. (2024).

Research result	Classification	Database
Research result	Classification	Scopus
Research output	Categorization	
Research finding	Categorisation	
Scientific result	Readiness	
Scientific output	Maturity	
Scientific finding		

The study identified five relevant publications presenting classification approaches or models for research results, leading to three distinct classification strategies. Consecutively, the study researched classification models used in the German research community by contacting one university (Karlsruhe Institute of Technology (KIT)), two research societies (Fraunhofer Society and Helmholtz Association), one research academy (acatech), and the German Federal Ministry of Education and Research (BMBF[1]). This analysis did not result in any further classification models for research results.

The study developed a classification model for research results, combining the findings of both systematic literature reviews. To conclude, the study conducted an initial evaluation of this classification model. Therefore, the study interviewed four researchers from different engineering disciplines to collect the research results they

[1] Bundesministerium für Bildung und Forschung

produced in their projects. Table 6.3 presents the research projects analyzed. All of them are part of the IRTG 2078 (cf. Section 4.2).

Table 6.3: IRTG research projects used for initial evaluation of the research result classification model. Adapted from Kempf et al. (2024).

Project number	Topic	IRTG research area
#1	Design method development in computer-aided engineering for shape and topology optimization of composite material parts (LFT-D – Long Fiber Thermoplast Directmolding)	Design
#2	Processing and production of composite parts in LFT-D processes	Technology
#3	Characterization of LFT-D composite material systems	Characterization
#4	Viscoelastic modeling and simulation of LFT-D composite material systems	Simulation

Section 6.3 presents the results of the second systematic literature review and the developed research results classification model.

6.2 The Various Types of Research Results

As shown in Table 6.4, the study allocated 33 types of research results to the five clusters: *publications*, *prototypes*, *equipment*, *data*, and *experience*. Appendix E shows the complete list of research result types described in the literature.

Table 6.4: Distribution of the identified research result types to the five clusters: publications, prototypes, equipment, data, and experience.

Publications	Prototypes	Equipment	Data	Experience
17 types	8 types	8 types	2 types	5 types

Figure 6.3 and Figure 6.4 present the five clusters, providing a short description, characteristics, and some examples of result types for each cluster.

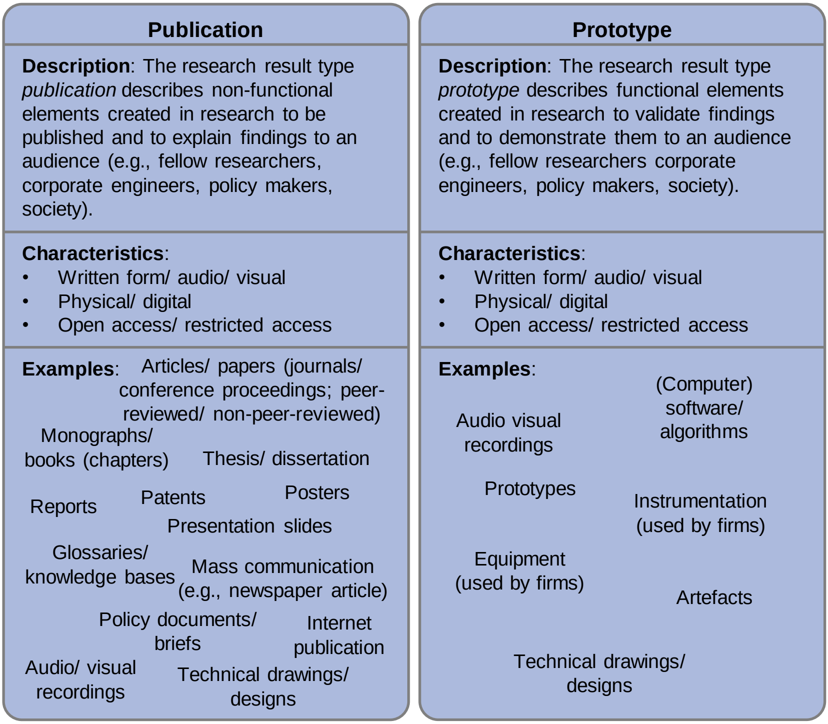


Figure 6.3: Research result clusters *publication* and *prototype*: Description, characteristics, and examples of the clusters. Based on Kempf et al. (2024).

The boundaries of the clusters prototype and equipment are somewhat permeable. Researchers can use the research results generated as a prototype as scientific equipment at a later stage (e.g., an in vitro optical sensor prototype used for measurements in scientific experiments). In the same way, researchers can use the research results generated for further use in research activities (equipment) as a prototype, e.g., for technology transfer. Thus, depending on the actual intention and point of view, the same (physical or immaterial) object can simultaneously serve as a prototype or equipment. Furthermore, researchers can present the same research result using multiple result types. For example, researchers often (but not always) use publications to describe or present research results of another type to an audience (e.g., in articles or presentations).

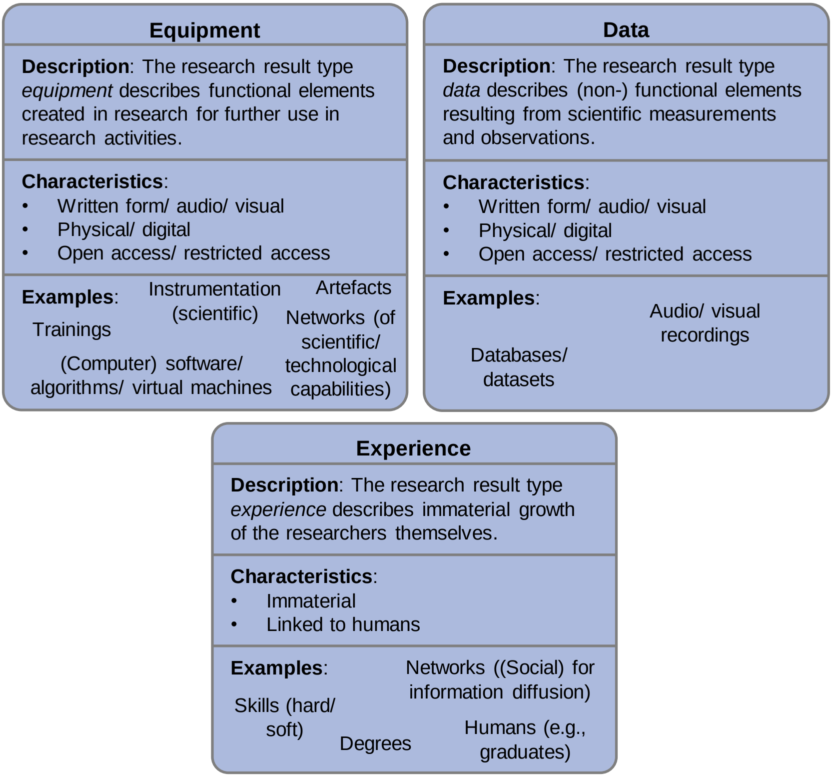


Figure 6.4: Research result type clusters *equipment*, *data*, and *experience*: Description, characteristics, and examples of the clusters. Based on Kempf et al. (2024).

6.3 Research Results Classification Model

Table 6.5 shows the three classification strategies the study identified through the systematic literature review. The analysis of these classification strategies shows a one-sided focus on either the bibliographic classification of publications (focused on papers and books) regarding their subject area and topic or on the maturity/ readiness level of technologies. Both classification metrics widely neglect the research results of the respective other types.

The third strategy distinguishes three kinds of social benefits to categorize research results. The decisive factor here is the applicability of the research results in products or processes with or without further necessary research steps. Table 6.5 gives an example to elucidate this understanding of contributing to social benefit directly or indirectly.

Table 6.5: Research results classification strategies described in the literature. Adapted from Kempf et al. (2024).

Classification strategy	Core aspects	Examples	Source
Bibliographic	Classification regarding subject/ research areas and fields	Essential Science Indicators (ESI): 22 research fields, SCOPUS: 27 subject areas: OECD Frascati 38 subordinate research fields, KAKEN-L3: 66 subject categories	(Gautam Pitambar, 2019)
Readiness/ maturity	Technology focus	Technology Readiness Level (TRL)	(Lee & Lee, 2014; Leisner & Johansson, 2019; Mankins, 1995, 2009)
Societal benefit	Direct or indirect application in products or processes	First: “discoveries may be applied directly to the creation of new processes or products.” Second: “outcomes may produce information that is an input into other […] research activities and, with modification and refinement, forms the basis for new products or processes.” Third: “outcomes may provide the information to improve processes or products […] primarily based on other scientific or technological discoveries.”	(David et al., 1992, p. 76)

Analyzing the German research community, the study indicates that German research institutions either use Technology Readiness Levels for research results' classification (Helmholtz Association, Karlsruhe Institute of Technology following European Commission (2015)) or no general classification approach exists on an institutional level (Fraunhofer Society, acatech, German Federal Ministry of Education and Research (BMBF)) (Kempf et al., 2024).

6.3.1 Designing the Initial Research Results Classification Model

Mankins (1995) Technology Readiness Levels (TRLs) are widely accepted in literature and practice to assess and describe the maturity of technologies. They formed the basis for further evolvement in the literature (e.g., European Association of Research and Technology Organisations, 2014; Heder, 2017; Revfi et al., 2020). However, the concept focuses mainly on technologies (cf. Subsection 2.3.2) and does not allow the holistic consideration of all research result types. Thus, this study generalized the Technology Readiness Levels to Research Readiness Levels (RRLs) in the first step. Table 6.6 presents these nine research readiness levels.

Table 6.6: Nine Research Readiness Levels (RRLs) to describe the maturity of any research result type based on Mankins (1995) Technology Readiness Levels. Adapted from Kempf et al. (2024).

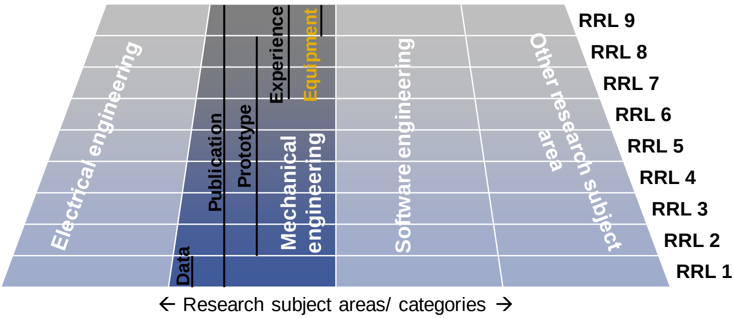
Research Readiness Level (RRL)	**Description**
RRL 1: “Basic principles observed and reported”	“RRL 1 covers results of the lowest maturity level. These are data from observations and reporting of basic principles. Thus, RRL 1 covers, e.g., data on the mechanical behavior of material systems, data from qualitative interviews, observations/ measurements of physical effects, etc. The results of RRL 1 can be the starting point for research of RRL 2 or used for validation activities of research at higher levels.” (Kempf et al., 2024, p. 640)
RRL 2: “Concept and/ or application formulated”	“Usually based on findings of RRL 1, RRL 2 covers, e.g., theories, concepts, or descriptions of possible future applications and represent hypotheses. The results of the second level are not yet proven but somewhat speculative at this point.” (Kempf et al., 2024, p. 640)
RRL 3: “Analytical and/ or experimental verification of critical function and/ or characteristic”	“RRL 3 contains research results with analytically or experimentally verified critical functions or characteristics. These are verified individually. For example, mathematical or software engineering-based concepts might be verified analytically, while, e.g., mechanical designs or material fracture models might have to be tested physically in experiments. This verification is usually done in a laboratory environment.” (Kempf et al., 2024, p. 640)
RRL 4: “Isolated validation in a laboratory environment”	“On RRL 4, the critical functions and characteristics are validated as a whole, including their interactions with each other. Results of RRL 4 are still validated in a laboratory environment.” (Kempf et al., 2024, p. 641)
RRL 5: “Isolated validation in a relevant environment”	“In contrast to RRL 4, [the] results of level 5 have to be validated in a relevant environment. However, this relevant environment can still be (partially) simulated.” (Kempf et al., 2024, p. 641)
RRL 6: “Integrated validation in a relevant environment”	“In case different research results shall be combined/ integrated with each other or already existing elements, these have to be validated as a combined system in a relevant environment to reach RRL 6.” (Kempf et al., 2024, p. 641)
RRL 7: “Integrated validation in the expected operational environment”	“In contrast to RRL 6, [the] results of level 7 have to be validated in the expected operational environment.” (Kempf et al., 2024, p. 641)
RRL 8: “Accomplished integration and clearance for operation”	“RRL 8 is a rather formal level of research results that achieved the clearance for "regular" operation in the intended environment. Depending on the research, clearance by external entities might be required.” (Kempf et al., 2024, p. 641)
RRL 9: “Actual successful operation”	“RRL 9 contains results that are successfully operated in their final environment. Since research facilities usually do not directly offer "products" or "systems" to society, these results will usually be operated within the research itself. For example, the test benches to be used for validation/ characterization activities (e.g., to achieve RRL 5 for another research result) could be such results of RRL 9. However, research facilities might offer services such as qualification programs or technical systems such as test facilities to society or companies.” (Kempf et al., 2024, p. 641)

The study aimed to design these research readiness levels to be abstract enough to cover any type of research result within engineering research. While the technology readiness levels only cover technologies (Revfi et al. (2020) extended it to designs, too), the research readiness levels also cover other results, such as design methods. The study used the “distance to societal benefit” similar to David et al. (1992) to measure readiness. The higher the research result’s research readiness level, the closer to societal benefit. Thus, “basic” research results are of lower readiness levels. Examples are the results of natural sciences such as physics (e.g., observations, hypotheses, theoretically proven theories). These results serve as input for other research activities, climbing the readiness levels with their results. For example, engineering research picks up physical effects to develop new technologies. As shown in the definitions of research readiness levels, validation activities are necessary to increase readiness levels.

Usually, research institutions do not offer systems or services directly to society. Companies will use research results (from different readiness levels) as reference system elements within their engineering activities. Examples include technological results, such as new lightweight material systems incorporated into corporate products available to society. The same applies to research results, such as design methods and process development advancements. Companies utilize these research results to enhance their engineering capabilities or provide their corporate customers with new engineering methods or tools. Thus, research results usually cannot reach the highest research readiness level (RRL nine), but for some exceptions, such as mass communications. Research results that usually reach RRL nine are the results of the type equipment that researchers develop for operation in research activities themselves.

Society benefits from research results with a high research readiness level either directly (e.g., through technological results) or indirectly (e.g., through methodological advancements or research results used in the research projects themselves). Research institutions do not conduct research in isolation. Research projects frequently involve companies and even society (e.g., as the end users). Researchers engage companies and society more intensively at higher research readiness levels, particularly when developing new technologies. In design research, specifically in studying the design process as defined by Blessing and Chakrabarti (2009), it is essential to continuously consider real-world environments and corporate and/ or societal requirements depending on the project from the beginning.

Figure 6.5 presents the initial version of a holistic classification model for any type of research result. The model combines the subject-specific categorization of research findings with a sorting regarding their maturity/ readiness levels. The vertical segments of the model represent distinct fields of research/ subject areas to incorporate the bibliographic aspect in the model and to provide an overarching structure. The horizontal tiers represent the research readiness levels. Being a cut pyramid, this model indicates the general reduction of the amount of research results on higher readiness levels. Simultaneously, results on lower levels form the basis of higher-level results.



RRL 1: Basic principles observed and reported; **RRL 2**: Concept and/ or application formulated; **RRL 3**: Analytical and/ or experimental verification of critical function and/ or characteristic; **RRL 4**: Isolated validation in a laboratory environment; **RRL 5**: Isolated validation in a relevant environment; **RRL 6**: Integrated validation in a relevant environment; **RRL 7**: Integrated validation in the expected operational environment; **RRL 8**: Accomplished integration and clearance for operation; **RRL 9**: Actual successful operation

RRL: Research Readiness Level

Figure 6.5: Initial research results classification model. The model combines a bibliographic subject area-focused categorization with assessing the research result’s readiness level. Adapted from Kempf et al. (2024).

Figure 6.5 highlights the research field of mechanical engineering, matching the different research result types with the different research readiness levels. Per the definition of research readiness level one, research results of the cluster *data* can only be at this level. However, data research results can be input for other research activities, including validation. Research results of the cluster *prototype* reach from levels two to eight. This cluster cannot reach level nine since such research results always serve a demonstration or validation purpose. The actual successful operation of the research result in the final environment defines level nine. Research results of the cluster *experience* cover levels seven to nine.

The classification of the immaterial, human-linked research results experience might seem technical. However, skills, etc., are validated by, e.g., certificates or degrees.

If the carrier (researcher) of research results of the cluster experience stays in research, these results reach level nine, too, as they are “operated” in their final environment. The research results of the cluster *equipment* are on level nine by definition, as researchers create these results to use in further research activities. *Publication* is the only research result cluster that can cover all nine research result levels, as publications can also describe any other type of research results.

The research result types of the cluster equipment differ from the other clusters regarding their social benefit. While the other research result types come closer to application with direct societal impact, research results of the cluster equipment have their final environment in research (a requirement for level nine) but thus provide societal benefit indirectly only, as they enable further research activities.

6.3.2 Initial Evaluation of the Research Results Classification Model

The study collected exemplary research results from four research projects (cf. Table 6.3 in Section 6.1) to evaluate the classification model initially. Table 6.7 shows an excerpt of the collected research results, their allocation to the research result type clusters, and the research readiness level. Appendix E shows the complete list and allocation of the collected research results.

All research projects cover engineering research and are part of the IRTG 2078 (cf. Section 4.2). Applying the definitions of the research readiness levels to the collected research results proved the model's general applicability to rate the research results' maturity. The general term *research result* and reference to the specific environments (e.g., laboratory environment, relevant environment, or actual operation environment) enable the classification of all collected research results. However, the actual classification of individual results requires a good understanding of the result. Otherwise, judging, e.g., the completed validation activities, is impossible. As already postulated before, the clusters of research result types proved to be permeable and view-point depending. For example, the study classified the Python scripts of project one as prototypes because they are part of the overall targeted result of the research project (optimization procedure), which is a prototype in the end. However, other research projects could also use the scripts for format conversion, making it a research result of the cluster equipment (cf. the coded scripts in project three).

Another example is the STL-files of plastificat in project two. In the project, these results are “just” data. However, if used for communication or to validate the production process, it could be a prototype, too.

Table 6.7: Excerpt of research results to initially evaluate the classification model. Allocation of research results from four research projects to the research readiness levels. Based on Kempf et al. (2024).

Project number	Research result	Cluster	RRL	Reasoning
#1	Optimization procedure (digital coupling model) of optimization and design tools implemented on a workstation	Prototype	2-6	Researcher evolved the procedure gradually, producing intermediate results on different maturity levels
#1	Conference publications of the optimization procedure	Publication	2-6	See above
#1	Scripts to couple different simulation and design tools, programmed in Python code	Prototype	7	Integrated into and validated within the optimization procedure
#2	Conference publication of recommendations for quality management and assessment for machinery manufacturers	Publication	7	Validated on the commercial machinery used by the researcher
#2	Prototype of monitoring technology to monitor the quality of the produced parts	Prototype	6	No integration into the machinery during the project
#2	STL-files (images) of plastificat	Data	1	
#2	Seminars (presentation, handout) on the processing for practitioners	Publication	9	Seminars currently offered to practitioners
#3	Modeling approaches/ hypotheses for material behavior description (algorithms on a server)	Prototype	4	Validated in a laboratory environment
#3	Coded scripts for data analysis	Equipment	9	Used in the research project
#4	Mathematic model (differential equations) including the material parameters for viscoelastic modeling of, e.g., polyamide (PA) implemented on a workstation	Prototype	4	Validated in a laboratory environment using experimental data
#1, 2, 3, 4	Networks with fellow researchers and corporate partners	Experience	9	
#1, 2, 3, 4	Bachelor and master graduates	Experience	8, 9	Graduates start working in practice
#1, 2, 3, 4	Bachelor and master degrees	Experience	8	Certificates of the graduates attesting the skills and knowledge

The first result of project one, the optimization procedure for coupled shape and topology optimization, nicely illustrates the maturing of research results during research projects. Starting on a low level, the researchers increased the readiness level of the optimization procedure through iterative analysis (validation) and synthesis activities. Furthermore, the study also proved that most of the research results of a cluster other than publication were also (part of) conference or journal publications (cf. project one's first two results in Table 6.7).

This evaluation is no extensive validation but an initial evaluation of the model. It illustrates the principal applicability of the model for categorizing research results within engineering research projects such as those conducted within the IRTG 2078. An additional validation study covering the research results of representative research projects would be necessary for generalization and holistic validation within all engineering fields. Nevertheless, the study carefully selected the research projects to represent a wide range of research fields. For example, research project four is of a quite theoretical nature, resulting in hypotheses and mathematical material models as research results. These results are comparable to the resulting hypotheses or observations of natural sciences describing natural effects or laws. Therefore, the study designed the initial classification model in an open manner to enable the inclusion of further research fields later on.

6.4 Conclusion

Research spans a heterogeneous spectrum of different research fields that produce a huge variety of different research results. In Chapter 6, this thesis researched the different types of research results and their possible classification. Thus, this chapter answered the following research and sub-research questions:

RQ2. How can research results be classified to facilitate their exploration as reference system elements in corporate product engineering projects?

- RQ2.1. What types of results are generated in research, and what are their characteristics?
- RQ2.2. How can the results from research be sorted in a classification model?

This thesis followed a literature-based approach combined with a case study-based initial evaluation to answer the research questions. Figure 6.6 summarizes the research approach and the core results of Chapter 6.

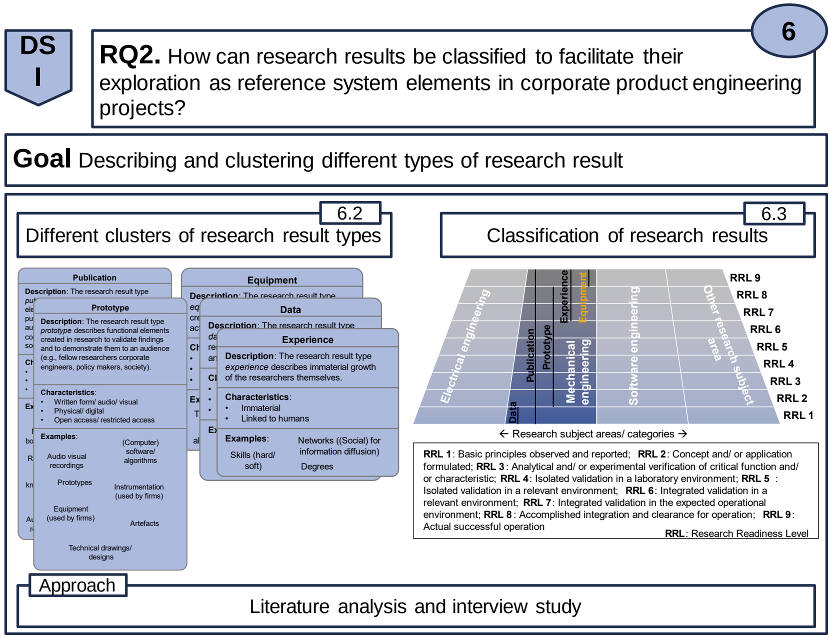


Figure 6.6: Summary of the objectives, approach, and results contributing to the second part of the Descriptive Study I to develop an initial classification model for research results. The results are illustrated using icons and presented in detail in Figure 6.3, Figure 6.4, and Figure 6.5.

This study first identified 33 research result types based on the literature analysis and subsequently categorized them into five clusters:

- *Publications* serve to communicate and disseminate findings.
- *Prototypes* serve to demonstrate and validate findings.
- *Equipment* serves to set up experiments and conduct further research activities.
- *Data* are the result of scientific experiments and observations. They serve as a basis for further research activities and validation.
- *Experience* is linked to humans and represents the gain in knowledge and expertise of the researchers.

While the original goal of the first sub-research question (RQ 2.1) was identifying all types of research results, the literature analysis made it clear that the wide variety within the diverse research disciplines does not allow such a conclusive list. Thus, the study decided to form the five clusters collecting related result types. The initial evaluation of the classification model proved the applicability of the five clusters suitable for the context of this thesis.

In the second step, the study developed an initial classification model for research results combining bibliographic and maturity measures based on the literature analysis. Therefore, this study generalized the nine technology readiness levels according to Mankins (1995) to nine research readiness levels (RRL), including their definitions. The “distance to societal benefit” is central to measuring the maturity within the research readiness levels. Besides the bibliographic properties and maturity of research results, the classification model illustrates the general range of readiness levels for the different research result clusters.

While the technology readiness levels focus on technology only but can be applied to technology developed across research and corporate engineering alike, this study designed the research readiness levels applicable to all types of research results. Here, the research readiness levels focus on the results of research facilities only, not considering corporate research explicitly. However, there is no indication that it should not also apply to corporate research results.

As explained in Section 6.1, the study only identified six publications discussing research results and five publications discussing the classification of research results as their research subject. The study had to limit the search approach due to the widespread use of terms like “result” and “model” and their synonyms in scientific abstracts. This limitation might be one reason for the low number of identified contributions. On the other hand, the few crosslinks between these contributions and other relevant contributions lead to the conclusion that a scientific investigation of research results and their categorization has not received much attention within research so far. The comparison with classification approaches used within the German research community, which did not reveal any further classification approaches, gave the study confidence that it had covered all relevant classification models. Similarly, the initial evaluation of the classification model using research results from four highly diverse engineering research projects did not lead to the need for further clusters of research results, indicating the suitability of the defined clusters.

Using the results of the four distinct IRTG 2078 research projects covering the range of engineering research from theoretical mechanical engineering research, such as engineering mechanics, via the applied process and production engineering to engineering design methods, the study successfully evaluated the five clusters of research results and the overall classification model. This successful evaluation indicates the applicability of the classification model to engineering research. However, it does not allow the claim of a holistic classification model for research results of other research fields. Therefore, this study calls the model an initial classification model. The evaluation of the suitability in other research fields is still pending. Here, the nature of the results of some other research fields, such as physics, might not be too different from the examples given in the evaluation cases (e.g., hypotheses formulated as mathematical equations). Thus, with the general definition of the research readiness levels, the classification model might also be able to categorize the results of these research fields.

However, the core target of the developed classification model is to provide a solid basis for the categorization of research results meant to serve as reference system elements in corporate product engineering activities. Therefore, it provides a good starting point for scientifically investigating the various research results used as corporate reference system elements and their characteristics. Consecutively, this categorization provides the basis for developing targeted design support for including research results of different categories and maturity into the design of reference systems in corporate product engineering.

7 Using Research Results as Reference System Elements in Corporate Product Engineering

After Chapter 6 discusses the different types of research results in engineering research theoretically, this chapter completes the first Descriptive Study (cf. Chapter 4) and researches the actual use of research results as reference system elements in corporate product engineering in practice. Starting with the reasons for using research results as reference system elements in corporate product engineering, this chapter also focuses on the collection and application (transfer into the reference system R_i) of research results as reference system elements, including the corresponding challenges. Thus, this chapter answers the following research question (cf. Section 3.4):

RQ3. How do corporate product engineers search for and apply reference system elements from research, and what challenges do they face in this process?

The following three sub-research questions break down research question three to further operationalize it:

- RQ3.1. What are the reasons and triggers for using reference system elements from research?
- RQ3.2. Which approaches do corporate engineers follow to search for reference system elements in research and to apply them?
- RQ3.3. What challenges and barriers do corporate engineers face in searching for and applying reference system elements from research?

Figure 7.1 provides an overview of the goals and approach to assess the current search for and application of research results as reference system elements in corporate product engineering. After Section 7.1 introduces the research approach, Section 7.2 presents the reasons and triggers for corporate engineers to use research results as reference system elements. Next, Section 7.3 elucidates corporate engineers' methods and approaches to search for and apply research results as reference system elements. Section 7.4 presents challenges and barriers corporate engineers face when searching for or applying research results as reference system elements. Finally, Section 7.5 concludes the findings.

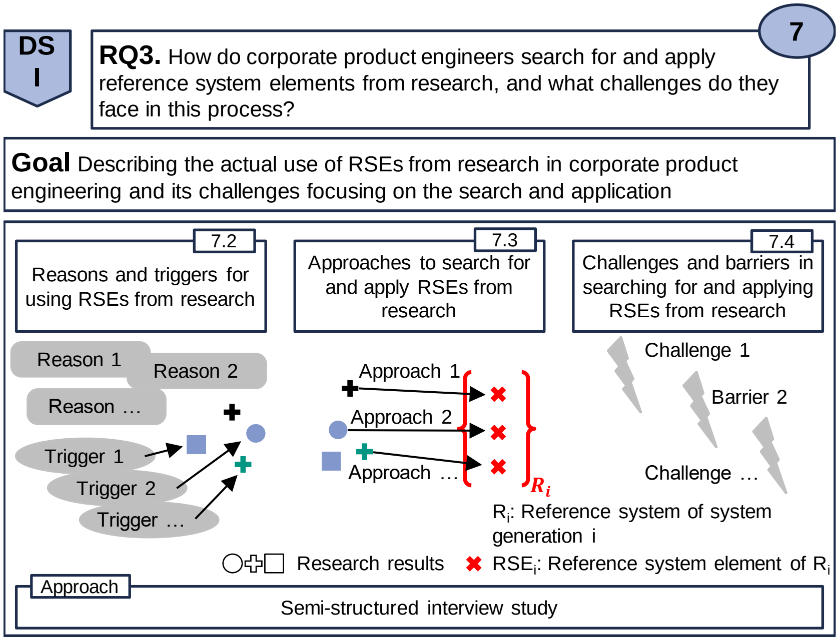


Figure 7.1: Overview of Chapter 7: The respective sections investigate the actual search and application of research results as reference system elements in corporate product engineering.

The results of this study were published at a scientific conference and journal as specified (Kempf, Schlegel, et al., 2023; Kempf, Thapak, et al., 2023). They were the subject of a student thesis that the author of this thesis co-supervised (Almeida, 2022)[1].

7.1 Research Approach

As shown in Figure 7.2, the study used an interview study following the semi-structured interview approach to answer the research questions. The semi-structured interview approach ensures the coverage of all relevant questions and

[1] Student thesis (unpublished)

topics throughout all interviews. It guarantees the comparability of the different interviews while maintaining flexibility within the individual interviews. (Blessing & Chakrabarti, 2009)

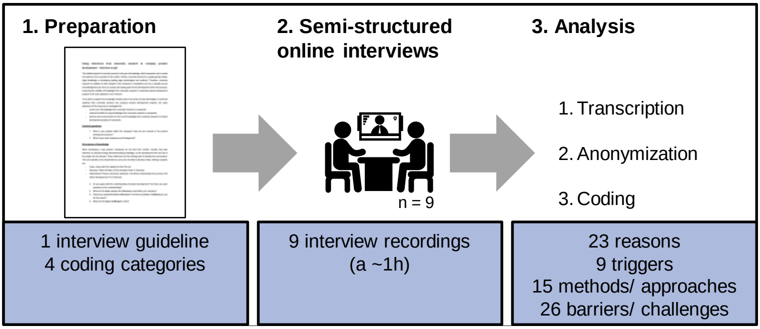


Figure 7.2: Approach to research the reasons and triggers, approaches and challenges of searching for and applying reference system elements from research.

In the preparation phase, the study designed an interview guideline consisting of 18 questions to structure the interviews. Appendix F shows the complete interview guideline. The guideline starts with a general section covering the background information of the interviewees. The main body of the interview starts with a section regarding the general use of reference system elements within their engineering activities before moving to the specifics of reference system elements from research. Furthermore, the study defined four coding categories to analyze the interviews, as shown in Table 7.1.

Table 7.1: Coding categories for the semi-structured interviews. Based on Kempf, Schlegel, et al. (2023), Kempf, Thapak, et al. (2023), and Almeida (2022)[2].

Code	Characteristics
Reasons	General arguments that favor the use of research results as reference system elements
Triggers	Specific circumstances that initiate the use (search for and application) of reference system elements from research
Methods/ approaches	Methods or approaches to search for and apply reference system elements from research
Challenges/ barriers	Challenges or barriers to searching for and applying reference system elements from research

In the interview phase, the study conducted nine semi-structured interviews in an online setting for approximately one hour based on the interview guideline. As interviewees, the study selected nine experts, as shown in Table 7.2. The interviewees were IRTG 2078 industry advisory board members[3] (cf. Section 4.2) supplemented by some additional experts.

Finally, the study analyzed the interviews by transcribing, anonymizing, and coding the interviews. The study identified 23 reasons, nine triggers, 15 methods and approaches, and 26 challenges and barriers following this approach. After Section 7.2 presents the identified reasons and triggers, Section 7.3 presents the methods and approaches. Third, Section 7.4 presents the challenges and barriers.

[2] Student thesis (unpublished)
[3] https://www.grk2078.kit.edu/244.php (June, 3rd 2024)

Table 7.2: Participants of the semi-structured interview study. Adapted from Kempf, Schlegel, et al. (2023), Kempf, Thapak, et al. (2023), and Almeida (2022)[4].

Interview #	Sector	Engineering discipline
I1	Automotive – tier 1	Pre-development/ innovation
I2	Materials	Material science/ process engineering
I3	Technology	Simulation
I4	Automotive – software supplier	Process simulation
I5	Automotive – tier 2	Product development
I6	Aerospace – tier 1	Data analytics
I7	Automotive – OEM	Simulation
I8	Materials	Material science
I9	Machinery	Product development/ data science

7.2 Reasons and Triggers for Using Research Results as Reference System Elements in Corporate Product Engineering

The study identified 23 reasons and nine triggers, analyzing the interviews. Here, the study considers reasons to be arguments of a more general nature that favor using research results as reference system elements in corporate product engineering. Triggers are the events/ concrete circumstances that initiate searching for or applying reference system elements from research.

As shown in Table 7.3, the study clustered the 23 reasons into seven categories: *Reliable sparring partners*, *open communication*, *high qualification*, *high-quality reference system elements*, *competitive advantage and mastering complexity*, *cost*

[4] Student thesis (unpublished)

and time efficiency, and *marketing and image*. Appendix F shows all the reasons identified, including the interview links.

Table 7.3: Distribution of the identified reasons from practice to use reference system elements from research to seven categories. Adapted from Kempf, Schlegel, et al. (2023) and Almeida (2022)[5].

#	Reason category	Number of reasons	Interview
1	Reliable sparring partners	2	I9
2	Open communication	3	I1, I6, I7
3	High qualification	1	I2, I9
4	High-quality reference system elements	6	I1-4, I6-9
5	Competitive advantage and mastering complexity	5	I2, I4, I9
6	Cost and time efficiency	4	I1, I2, I7
7	Marketing and image	2	I8, I9

The reasons within the first three categories all describe the positive aspects of research organizations and researchers as partners in engineering activities. Thus, these reasons are not specific to using reference system elements from research but are also valid for industry-academia collaboration in general. However, they also support the use of reference system elements from research in corporate product engineering.

- Reliable sparring partners: Interviewees state that research would offer reliable partners for continuous and long-term collaboration. Additionally, they stress the value of research partners for pushing (e.g., physical) limits in knowledge and technology (e.g., resilience of subsystems by material system exchange).
- Open communication: Interviewees state that they value open and neutral communication. Researchers would neither hide information nor follow political agendas. Furthermore, interviewees value the possibility of talking to researchers to acquire implicit knowledge when using their research results as reference system elements.
- High qualification: Interviewees value the high competencies and qualifications of the sparing partners from research.

The reasons collected in categories four and five summarize the positive aspects of using research results as reference system elements due to the quality of research

[5] Student thesis (unpublished)

results and their value in dealing with the increasing complexity of processes and systems.

- High-quality reference system elements: Interviewees state that research would offer a solid knowledge base with basic data and knowledge. Corporate engineers could use this knowledge base as a starting point to approach new applications, processes, or technologies. On top of that, research would offer detailed information on new technologies. Additionally, interviewees value that reference system elements from research would be free to use since they would not be protected by, e.g., intellectual property rights. Another quality of reference system elements from research would be their different point of view helping to overcome company blindness.
- Competitive advantage and mastering complexity: Interviewees state that research would be a great or even the only source for reference system elements and discussions, especially if the company is a technology leader within its field. This close interaction would be essential to solving highly complex problems and keeping up with the high development speed.

The last two categories summarize the positive aspects of including reference system elements from research into corporate product engineering regarding the engineering resources and the company's image or systems.

- Cost and time efficiency: Interviewees state that using reference system elements from research would offer the potential to reduce their own engineering cost and time compared to developing everything in-house. Additionally, the public funding available for collaborations would reduce the costs.
- Marketing and image: Interviewees state that the use of reference system elements from research could be used for advertisement and discussions with (potential) customers. Some interviewees also state that collaboration with research and using reference system elements from research could be used to improve the image of the company or systems developed.

While analyzing the interviewees' responses, the study noticed that not all reasons can be generalized for all research results. For example, not all research results are free to use but protected through, e.g., patents. Another example is the relatively high turnover rate of researchers within engineering research for doctoral candidates employed as scientific employees (approximately three to five years (Statistisches Landesamt Baden-Württemberg, 2022)). Only a few of them stay in research afterward. This high turnover seems to contradict the persistence of researchers as a collaboration partner. The interviewees named the high persistence as a collaboration partner as a reason. However, the institutions and professors are usually persistent. Thus, and due to the design of the interview study (explorative character of interviewing nine corporate product engineers), the study concludes that the presented reasons led to using specific research results as reference system elements in specific situations and cannot be generalized for all research results at all times. The study interprets the reasons as levers to improve the usability of research results as reference system elements.

Additionally, the study elucidates that the reasons for using research results as reference system elements in corporate product engineering are not result-type specific but apply to all types on a general level.

Table 7.4 presents the nine triggers, i.e., specific circumstances, that lead to searching for or applying research results as reference system elements in corporate product engineering identified in the interview study.

Table 7.4: Triggers from practice for searching for or applying research results as reference system elements in corporate product engineering identified in the interview study. Adapted from Kempf, Schlegel, et al. (2023) and Almeida (2022)[6].

#	Trigger	Interview
1	Customer requires functionalities not common in the field	I2, I5
2	Detailed principles and understanding necessary	I3, I9
3	Discovering a new technology with insufficient in-house expertise	I1, I3
4	Extending into new fields of application or processing	I2, I4, I6, I9
5	Other sources are blocked or do not offer solutions	I2, I9
6	Project or task with a high degree of novelty	I9
7	Reaching the limit of in-house capacities	I2, I6
8	Reaching the limit of in-house expertise	I1, I2, I4, I5, I6, I9
9	Unclear use case/ application of a new technology	I1

Most of the triggers named by the interviewees relate to the corporate engineers reaching their or the company's limit of expertise, either for new emerging technologies and knowledge, or technologies, functionalities, applications, and knowledge not common within their field. Other triggers that might initiate the search for reference system elements in research are if other sources for reference system elements are blocked or the limits of in-house capacities for development are exhausted.

[6] Student thesis (unpublished)

The comparison of the identified triggers with the reasons shows that these are related. For example, trigger seven mentions reaching the limit of in-house capacities as initiator for the search for suitable reference system elements in research. The sixth category of reasons (cost and time efficiency) represents the reduction of engineering resources (time and cost) on the general level, too.

The study did not identify specific relations of individual reasons or triggers to specific research result types (cf. Chapter 6).

7.3 Methods and Approaches for Searching for and Applying Research Results as Reference System Elements in Corporate Product Engineering

Corporate product engineers can follow different approaches or use different methods to search for reference system elements in research and include them in their reference system. This section presents the methods and approaches corporate product engineers use in practice based on the interview study (cf. Section 7.1).

Table 7.5 presents 15 methods and approaches corporate product engineers can follow to search for or apply reference system elements from research as identified in the interview study.

Table 7.5: Methods and approaches used in practice to search for and/ or apply reference system elements from research identified in the interview study. Adapted from Kempf, Thapak, et al. (2023) and Almeida (2022)[7].

Method/ approach to search for RSEs in research	**Method/ approach to search for or apply RSEs from research**	**Method/ approach to apply RSEs from research**
Participating in (scientific) conferences (I2-6, I8, I9)	Literature review (I1-5, I7, I9)	Collaborative projects (publicly funded or direct cooperation) (I2-9)
Personal networks (I3-6, I9)	Direct conversation (I1, I3, I5, I6, I8, I9)	Hiring former researchers (I2-5, I8, I9)
Attending fairs/ exhibitions (I2, I3)	Employing Ph.D. candidates/ doctoral researchers (I1, I3, I9)	Hiring university graduates (I5, I9)
Organizing research pitches (I3, I6)	Offering cooperative master/ bachelor theses (I4, I5, I7)	Offering internships to students (I7)
	Financing/ supporting Ph.D. candidates/ doctoral researchers at research institutes (I1, I4)	Organizing internal lectures (I6)
	Consulting experts as “translators” (I1)	

The study organized the methods and approaches into three categories: Methods and approaches to

- search for reference system elements in research.
- apply reference system elements from research.
- do both (search and apply the reference system elements).

The identified methods and approaches range from rather chance-based, such as participation in conferences or attending fairs, to highly structured approaches, such as literature reviews, collaboration projects, or cooperative theses for students and student jobs. Furthermore, the study discovered that eight of the 15 methods and approaches are human-centered, such as personal networks, direct conversations, and the employment of students, doctoral researchers, and graduates.

The study discovered that besides the literature review, all other results are relatively general approaches to searching for or applying reference system elements from research. The interviewees did not mention many concrete methods or tools, such

[7] Student thesis (unpublished)

as those identified for the Reference System Element Identification Atlas (cf. Section 5.2).

Figure 7.3 links the methods and approaches from practice to search for and apply reference system elements from research to the different research result clusters.

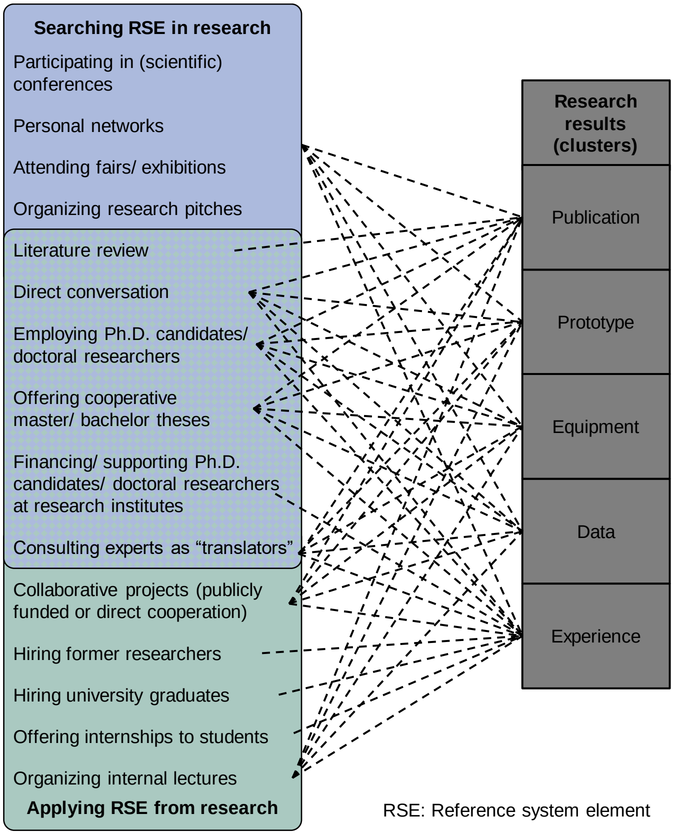


Figure 7.3: Methods and approaches used in practice to search for and/ or apply reference system elements from research linked to the clusters of research results.

Most methods and approaches qualify to handle the research results of all clusters. The only specific methods and approaches are conducting a literature review on the one hand and financing or supporting Ph.D. candidates or doctoral researchers, hiring former researchers, hiring university graduates, or offering internships to students on the other hand. A literature review serves to search for and apply publications (usually book, journal, or conference contributions). The other four methods/ approaches are all human-linked and serve to get hold of their experience.

7.4 Challenges when Searching for and Applying Research Results as Reference System Elements in Corporate Product Engineering

Searching for and applying reference system elements from research, corporate engineers face different barriers and have to overcome various challenges. Table 7.6 shows the identified 26 potential challenges and barriers mentioned by the interviewees. Here, the study categorized them into four groups: Challenges and barriers

- related to the specific research result.
- related to the nature of research.
- related to the company and corporate product engineers.
- related to the search and/ or application process.

Additionally, Table 7.6 illustrates if the challenges and barriers affect the search for reference system elements in research, application of reference system elements from research, or both. Appendix F provides short descriptions of all challenges and barriers.

The identified challenges and barriers are not always present in every situation when a specific corporate product engineer of one specific company looks for a reference system element in research or wants to integrate it into their reference system. Instead, these challenges and barriers represent a collection of potential challenges or barriers that can exacerbate the search for or application of reference system elements from research, occurring in various combinations.

Table 7.6: Overview of the 26 potential challenges and barriers from practice exacerbating the search for and/ or application of reference system elements from research clustered into four categories. Adapted from Kempf, Thapak, et al. (2023) and Almeida (2022)[8].

Related to the research result	**Related to the nature of research**	**Related to the company and/ or corporate engineer**	**Related to the search and/ or application process**
Unclear use case/ application[S] (I1, I4, I7)	High amount of research results[S] (I2)	High progressiveness[A] (I5, I8)	Difficult scalability[A] (I1, I2, I5, I6)
Unclear benefits bundle[S] (I1, I2, I4)	Unsatisfying intellectual property regulations[A] (I1, I3, I4, I8)	Lacking technological/ scientific expertise of management[A] (I6)	High time investment for implementation[A] (I1, I7, I9)
Unclear reliability/ maturity[A] (I2, I3, I5-9)	Neglected profitability[A] (I2, I6, I9)	High rigidity of engineers and company[S/A] (I1, I3, I5, I6, I8)	
Unfitting RSE environment[A] (I3, I6, I7, I9)	Long development time in research[A] (I1, I2)	Missing expertise[S/A] (I5, I6, I9)	
Neglected interdependencies of product and production[A] (I1, I2, I6)		Limited grasp[S/A] (I1)	
Neglected systemic interrelations[A] (I5, I6, I9)			
High disciplinarity[A] (I5, I9)			
Missing information[A] (I2, I3)			
Excessive positivity[A] (I3)			
High generality[A] (I9)			
Lacking professionalism[A] (I3)			
Insufficient consideration of corporate needs[S/A] (I1, I6-9)			
Unpopular research jargon[S/A] (I1, I4, I6, I7)			
High specificity[S/A] (I2, I5, I6)			
Unattractive representation format[S/A] (I1, I7)			

[S]Affects searching RSE; [A]Affects applying RSE; [S/A]Affects searching and applying RSE

While the challenges and barriers are distinct, some of them are connected. For example, *unclear use case/ application*, *unclear benefits bundle*, and *insufficient consideration of corporate needs* relate to each other. Also, the *limited grasp of corporate engineers*, the use of *research chargon*, and the *unattractive representation format* of research results influence each other.

Most challenges and barriers (15 out of 26) are directly associated with the research results. Challenges and barriers such as *unclear benefits bundles*, *unpopular research jargon*, or the *insufficient consideration of corporate needs* indicate that corporate engineers are not always the prime target group the researchers want to address with their results. Due to the current research system, other researchers and funding agencies are often the primary addressees of research results.

Figure 7.4 summarizes the findings regarding the challenges and barriers identified in the interview study. Therefore, it connects the challenges and barriers to the clusters of research results they affect. Challenges and barriers not connected to a cluster of research results can affect any type of research result. Here, all challenges and barriers related to the company or corporate product engineers are of a general nature and can affect the search for or application of all types of research results.

[8] Student thesis (unpublished)

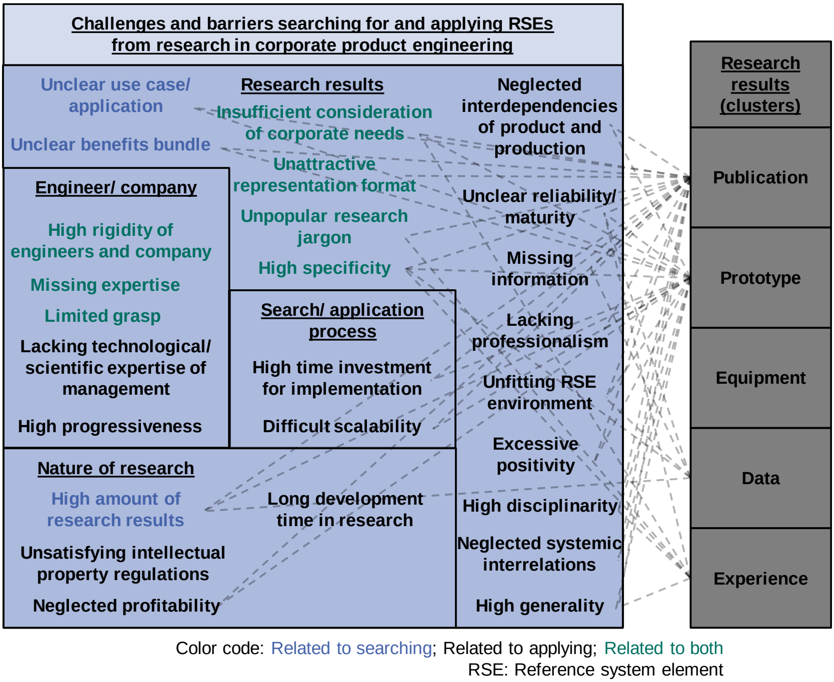


Figure 7.4: Descriptive model of challenges and barriers from practice exacerbating the search for and/ or application of reference system elements from research. Challenges and barriers not linked to a cluster of research results can affect all. Adapted from Kempf, Thapak, et al. (2023).

7.5 Conclusion

In Chapter 7, this thesis researched the current situation of searching for and applying reference system elements from research from the perspective of corporate product engineers. Thus, this chapter answered the following research and sub-research questions:

RQ3. How do corporate product engineers search for and apply reference system elements from research, and what challenges do they face in this process?

RQ3.1. What are the reasons and triggers for using reference system elements from research?

RQ3.2. Which approaches do corporate engineers follow to search for reference system elements in research and to apply them?

RQ3.3. What challenges and barriers do corporate engineers face in searching for and applying reference system elements from research?

This thesis conducted an interview study to answer the research questions. Figure 7.5 summarizes the research approach and the core results of Chapter 7.

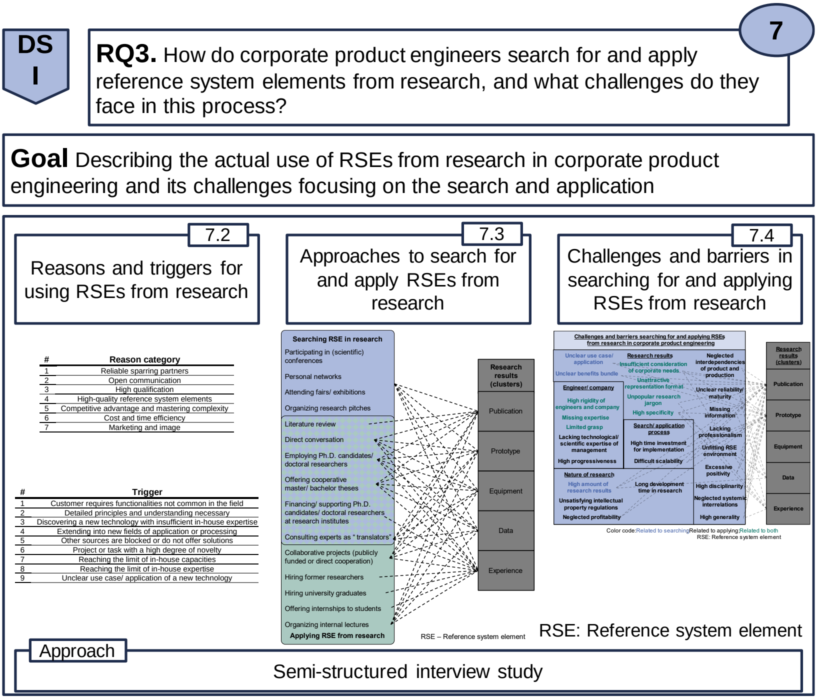


Figure 7.5: Summary of the objectives, approach, and results contributing to the second part of the Descriptive Study I to research the corporate perspective of searching for and applying reference system elements from research. The results are illustrated using icons and presented in detail in Table 7.3, Table 7.4, Figure 7.3, and Figure 7.4.

Following the semi-structured interview study with nine experts from corporate engineering practice, this study emphasizes three aspects. First, the thesis investigated the general reasons for corporate product engineers to use reference system elements from research and concrete triggers that initiate the search for reference system elements in research. Here, the study identified 23 reasons categorized into seven clusters and nine triggers. The study discovered that the triggers prompt corporate product engineers to look into research for reference system elements but are not connected to specific types of research results. These absent connections indicate the value of the diverse research result types beyond actively commercialized ones such as patents. Hence, these findings provide valuable background information on why and when corporate product engineers turn to research for reference system elements. Thus, these findings provide necessary input for developing methodological support to systematically assist corporate product engineers in complementing their reference system with elements from research. The identified reasons provide a baseline for research as they represent the research's and its results' valued qualities. Consequently, the reasons can serve as optimization criteria for research to produce results that are well-suited as reference system elements in corporate product engineering.

Second, the thesis researched the methods and approaches corporate product engineers follow to search for and apply reference system elements from research. Here, the thesis identified 15 methods and approaches in total that corporate product engineers can use to search for or apply reference system elements from research. These methods and approaches range from chance-based to highly structured, and from independent to highly collaborative. Four of the identified methods and approaches relate to the search for reference system elements in research. Five other methods and approaches focus on applying the reference system elements identified in research to the reference system. Finally, the last six methods and approaches support both searching for and applying reference system elements from research. Some methods and approaches qualify to address all clusters of research results, but not all of them do.

Comparing the findings of this study with the findings of Section 5.2 suggests that the process of searching for and applying reference system elements from research holds potential for methodical support. The Reference System Element Identification Atlas (cf. Subsection 5.2.2) offers about 20 more methods and tools described in the literature that can, in theory, be used to search for and apply reference system elements from research. In conclusion, the findings provide the basis for developing methodic support for corporate product engineers to select the appropriate method or approach to search for and apply reference system elements from research.

Third, the study elucidates 26 potential challenges and barriers for corporate product engineers when searching for or applying reference system elements from research. While three challenges and barriers can exacerbate searching for reference system elements in research only, 16 can exacerbate applying reference system elements from research into the reference system. The final seven challenges and barriers can exacerbate both searching for and applying reference system elements from research.

Comparing the challenges and barriers to searching for or applying reference system elements from research with the reasons to use these elements showed that some of them are complementary. For example, one reason mentioned in the interviews was that research results would be free to use in terms of intellectual property (part of the reason category high-quality reference system elements). However, unsatisfying intellectual property regulations were mentioned as a barrier, too. This potential contradiction elucidates the ambivalence of the needs in different situations (not all research results are free to use; it is not always desired that the research result is free to use for everybody). Thus, addressing the challenges and barriers requires situation-specific, adaptable methodical support.

Fifteen of the challenges and barriers are directly linked to specific research results. Thus, these challenges can serve as the basis for researchers to improve the usability of their results as reference system elements. Five challenges and barriers are directly linked to the company and its engineers. Therefore, the knowledge about these challenges and barriers can serve as the basis for companies and engineers to improve themselves. However, the close collaboration of researchers and corporate product engineers is the most promising approach to address most challenges and barriers. Here, policymakers and, subsequently, funding agencies can shape the environment.

Summarizing all findings, Chapter 7 provides first insights into the current practice of using reference system elements from research in corporate product engineering. Due to the design of the interview study, it can not claim holistic validity. However, the thesis designed the study to research the status quo exploratively. It conducted nine interviews with selected experts from different branches to cover the viewpoint of corporate product engineers from practice that would complement the scientific literature. Here, the study focused on automotive and material science due to the research environment IRTG 2078. However, the study selected interview partners from diverse engineering disciplines (data analytics and simulation via material science and process development to pre-development/ innovation and product development) to strengthen the explorative potentials. Thereby, the study was able to identify a broad range of reasons and triggers for corporate product engineers to use reference system elements from research in their work. It is important to mention that these reasons and triggers are not omnipresent. The reasons are not valid for all research results (as some of the challenges demonstrate) but represent general advantages the specific research results had. In the specific cases, the reasons favored the use of these elements. However, the first step of methodical support for integrating research results into corporate reference systems should be a thorough situation analysis using the reasons and triggers as input.

Analyzing the methods and approaches corporate product engineers can follow to search for or to apply reference system elements from research resulted in mostly general approaches. Thus, targeted methodical support in selecting general approaches and specific methods has much potential.

Finally, the identification of 26 potential challenges and barriers represents the starting point for developing methodical support for integrating research results into corporate reference systems. They are the levers to be tackled to improve the usability of research results as reference system elements in corporate product engineering and, on the other hand, the successful integration into the systems in development of the companies. Thus, the most relevant stakeholders to improve the usability of research results are, firstly, the companies and their product engineers since they are the first customers of the research results and responsible for the integration. Second, research facilities and their researchers develop the research results and, thus, can appropriately shape them to serve as input for the reference system in corporate product engineering. Both stakeholder groups must work together closely to develop design support for the use (search for and application) of reference system elements from research. Finally, research policymakers and, subsequently, the funding agencies establish the environment of research and can steer the direction of research activities as well as the principle design of research results.

8 Development of Recommendations to Improve Research Results' Usability as Reference System Elements in Corporate Product Engineering

Based on the results and implications of the previous chapters, this chapter develops recommendations to improve the usability of research results as reference system elements in corporate product engineering. These recommendations aim to address research as the source and donor, corporate engineering as the sink and recipient of reference system elements, and research policy as the overarching framework. This consideration leads to the three relevant target groups of the recommendations: *corporate product engineers and companies*, *researchers and research facilities*, and *funding agencies and (research) policymakers*. Thus, as the Prescriptive Study (cf. Chapter 4), this chapter answers the following research question (cf. Section 3.4):

RQ4. What are suitable recommendations to improve the usability of research results as reference system elements in corporate product engineering?

The following three sub-research questions break down research question four to further operationalize it:

- RQ4.1. How can corporate product engineers be motivated for and supported in searching for and applying RSEs from research?
- RQ4.2. How can researchers be motivated and supported to increase the usability of their research results as RSEs in corporate product engineering projects?
- RQ4.3. How can funding agencies/ policymakers positively influence the usability of research results as RSEs in corporate product engineering projects?

Figure 8.1 provides an overview of this chapter. After Section 8.1 presents the research approach, Section 8.2 presents the recommendations for the three target groups: corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers. Section 8.3 concludes the recommendations.

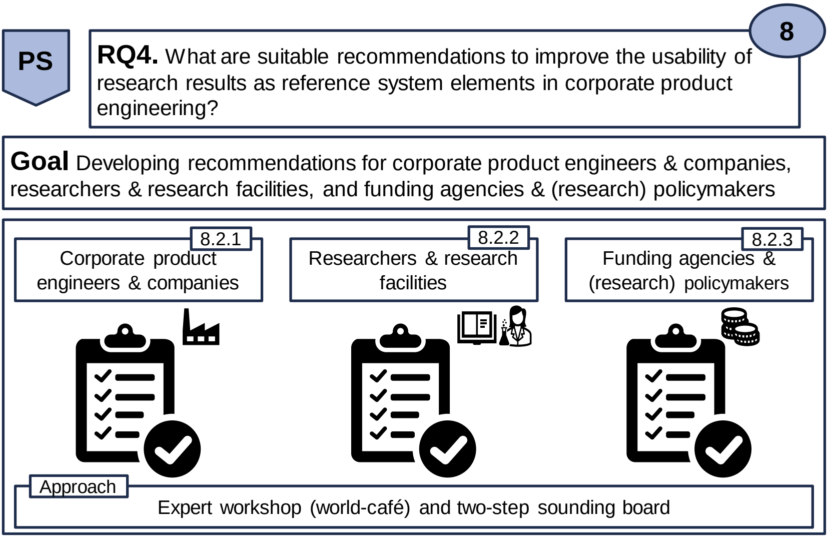


Figure 8.1: Overview of Chapter 8: To answer the fourth research question, the respective sections develop recommendations for the three target groups: corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers.

The results of this study were published in a scientific journal as specified (Kempf et al., 2025). They were the subject of a student thesis that the author of this thesis co-supervised (Molz, 2024)[1].

8.1 Research Approach

This study followed a multi-method approach to answer the fourth research question. As illustrated in Figure 8.2, the study first conducted an on-site workshop in a world-café[2] setting to develop and collect different measures to improve

[1] Student thesis (unpublished)

[2] The world-café is a round-based workshop setting for larger groups. The group is split into smaller teams working on a specific task and fixating their results in a more intimate setting (coffee table). In multiple rounds, they move to the other tables,

research results' usability as reference system elements in corporate product engineering. In the second step, the study used the sounding board method[3] to develop and improve the final recommendations based on these measures.

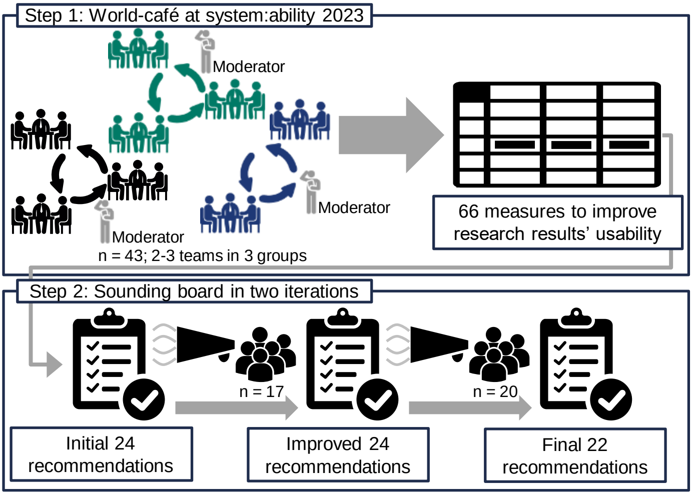


Figure 8.2: Approach to develop recommendations to improve research results' usability as reference system elements in corporate product engineering for the three target groups: corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers. Adapted from Kempf et al. (2025).

In the first step, this study developed and collected 66 measures to improve research results' usability as reference system elements in corporate product engineering based on the challenges and barriers of Kempf, Thapak, et al. (2023) (cf. Section 7.4). Therefore, this study conducted an on-site world-café workshop with 43 experts

discuss the other tasks, and add to the result documentation. (Cf. Brown and Isaacs (2005) and Tan and Brown (2005))

[3] The sounding board method is a method to collect feedback structuredly and efficiently. A group of experts (the sounding board) comments and gives feedback (sound) to an input presented to them. This feedback is incorporated into the further course of the project. (Cf. Dittrich-Brauner et al. (2013) and Walter et al. (2017))

during the system:ability conference 2023[4]. The one-hour workshop involved experts from research, corporate product engineering, as well as research funding, management, and policymakers. Thus, the study's participants represented all relevant views for deriving measures to improve research results' usability as reference system elements in corporate product engineering. The system:ability is the perfect setting for this workshop as all experts work on "Advanced Systems Engineering for the value creation of tomorrow". Thus, they are motivated intrinsically to apply their research projects' results to corporate engineering. The study split the 43 experts into three groups with one moderator each to organize them. Here, the study split groups one and two into three teams and group three into two teams. In the first round of two, each team of groups one and two discussed and developed measures for one of three target groups: corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers. The teams of group three did not work on measures for corporate product engineers and companies. The participants documented all results. In the second round, all but one team member each moved to the results of another team within their group. In this round, they discussed the first round's results with the remaining expert and added their comments and inputs.

To conclude the workshop, one team per group presented their measures for one of the target groups and collected the plenary's final comments on their measures. In the postprocessing, the study sorted all measures, removing duplicates. This resulted in 16 measures addressing corporate product engineers and companies, 24 addressing researchers and research facilities, and 26 addressing funding agencies and (research) policymakers. Table 8.1 shows an excerpt of the condensed and sorted measures gained from the workshop. Appendix G provides a complete list of all measures.

[4] The system:ability 2023 was a conference organized by the AdWiSE team, including this thesis's author. During the conference, AdWiSE connected research projects funded by the BMBF and enabled the communication and exchange of results. All projects were funded by the initiative "Handling the complexity of sociotechnical systems – a report on Advanced Systems Engineering for the value creation of tomorrow (PDA_ASE)" of the research program: "Innovations for Tomorrow's Production, Services, and Work". All workshop participants were members of such research project consortia or managing them for the BMBF.

Table 8.1: Excerpt of measures addressing the three target groups. Adapted from (Kempf et al., 2025).

Measures for corporate product engineers and companies	Measures for researchers and Research facilities	Measures for funding agencies and (research) policymakers
Translating research question	Stakeholder-specific preparation of results	Requesting specific use cases
Mindset for failures	Presentation of partial results via success stories	Transparent communication of the shift in goal/focus
Dismissing the need for ROI in research projects	Publication of learnings from "failures"	Offering (flexible) funding for demonstrators
Central repository for research results[F/P, R]	Ensuring quality and use case relation by, e.g., using reporting templates for research results or standardizing the preparation of methods (e.g., methods development kits)	Enabling easy and direct exchange between policymakers, companies, and research
Preparation and presentation of the concepts in the corporate context to present to the management	Developing competencies (integrated with company and research) such as "transfer to teaching" using, e.g., competency navi	Requesting specific work packages for transfer within projects (+ funding of, e.g., transfer platforms)

[R] Relevant for researchers/ research facilities, too.
[F/P] Relevant for Funding agencies/ (research) policymakers, too.

The study used these 66 measures and the gained expertise from the previous studies as input to develop the first version of 24 recommendations.

In the second step, the study applied the sounding board method with 37 experts in two consecutive iterations to evolve and initially evaluate the recommendations. The study conducted the first iteration in a one-hour online workshop using an online whiteboard tool with 17 participants. All 17 participants were engineering design science researchers focused on engineering methods and had industry-academia collaboration experience[5]. Split into two groups with a moderator each, all participants sounded half the recommendations by writing sticky notes on the online board and oral comments. The study incorporated all feedback to advance the recommendations, resulting in 24 improved recommendations.

[5] All participants were part of this thesis author’s research group.

In the second iteration, 20 selected external experts from all three target groups of the recommendations[6] sounded the 24 improved recommendations in written form. The experts could choose between document-based (text-file via email) and online-form-based sounding according to their preferences. Figure 8.3 shows the allocation of experts to the recommendations. Each expert sounded 13 of the recommendations to reduce the necessary time investment. One expert of the corporate engineers, one of the researchers, and three of the funding agencies sounded all recommendations.

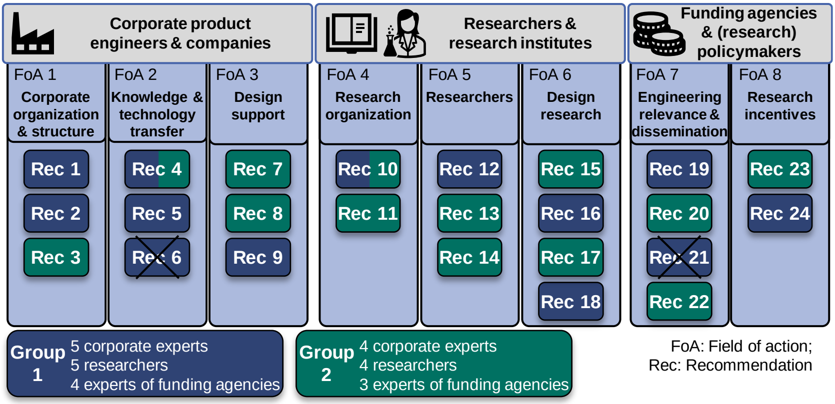


Figure 8.3: Allocation of the second sounding board members to the recommendations. The study rejected the initial recommendations 6 and 21 based on the feedback. Adapted from Kempf et al. (2025).

Additionally, the study asked the second sounding board to rate the recommendations' relevance using a six-point Likert scale (1 – non-relevant to 6 – very relevant). The study used all comments and feedback from the second sounding board iteration to improve the recommendations further. The study removed the initial recommendations 6 and 21 because the sounding board deemed

[6] The second iteration's sounding board panel did not overlap with the first panel. Eight experts were leading experts in large and medium-sized German companies in automation technology, automotive, and industrial engineering. Another eight experts were leading German design and engineering science researchers. The remaining four were part of an industry-driven network and German funding agencies working with the BMBF.

them trivial or already implemented. Thus, the study developed the final set of 22 recommendations presented in the following section.

8.2 Recommendations to Improve Research Results' Usability as Reference System Elements in Corporate Product Engineering

As Figure 8.4 shows, this study provides eight fields of action summarizing 22 recommendations to improve the research results' usability as reference system elements in corporate product engineering. Fields of action one, two, and three address corporate product engineers and companies. Subsection 8.2.1 presents their recommendations. Fields of action four, five, and six address researchers and research institutes. Subsection 8.2.2 presents their recommendations. Finally, fields of action seven and eight address funding agencies and (research) policymakers. Subsection 8.2.3 presents their recommendations.

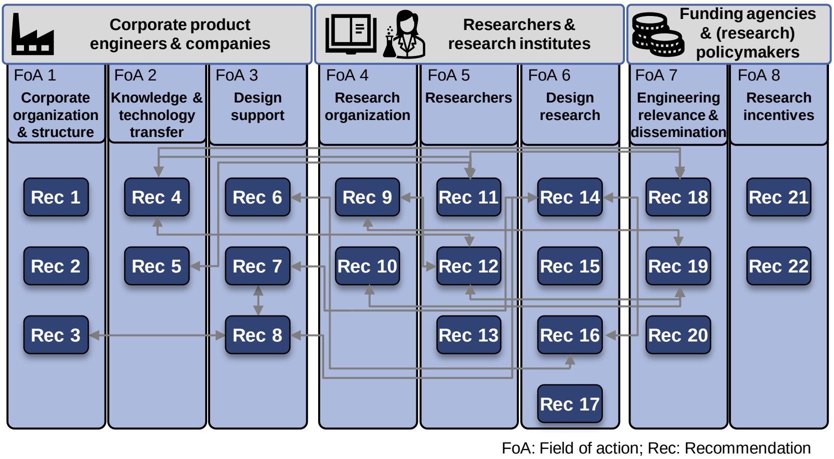


Figure 8.4: Overview of the final 22 recommendations in eight fields of action address three target groups to improve research results' usability as reference system elements in corporate product engineering. The grey arrows illustrate the interactions. Adapted from Kempf et al. (2025).

The recommendations are stand-alone. However, there are many interrelations and beneficial influences between the recommendations, even across the three target groups. For example, industry-academia teams should collaboratively address the recommendations of fields of action 3 and 6.

Figure 8.5 shows the recommendations' relevancy assessment by the second sounding board. The panel rated all 22 selected recommendations as rather relevant to very relevant.

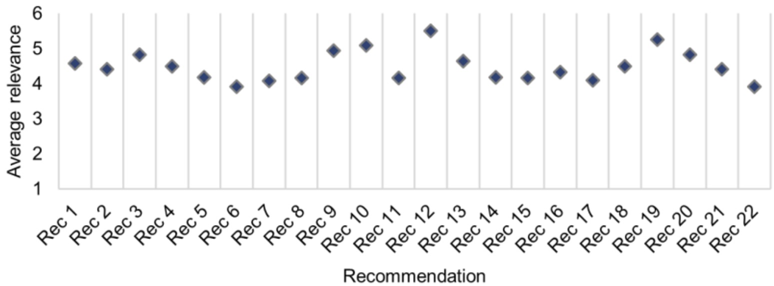


Figure 8.5: Recommendations' relevancy assessment of the second sounding board on a six-point Likert scale (1 – non-relevant to 6 – very relevant). The panel rated all 22 selected recommendations as rather relevant to very relevant. Adapted from Kempf et al. (2025).

The starting point and boundary conditions differ across the different companies, research facilities, and funding agencies/ programs. Some already follow some recommendations, while others do not. Therefore, the provided 22 recommendations offer a basis to improve the usability of research results as reference system elements in corporate product engineering with various adjusting screws. Obviously, the different addressees must consider their specific situation, including their goals and boundary conditions, first, to select the recommendations most valuable for their needs, and second, to define the concrete implementation of the recommendations. A research collaboration can help to define the implementation strategy.

8.2.1 Recommendations for Corporate Product Engineers and Companies to Improve Their Use of Research Results as Reference System Elements

Figure 8.6 provides an overview of the recommendations for corporate product engineers and companies to improve their use of research results as reference system elements. The first three fields of action collect eight recommendations.

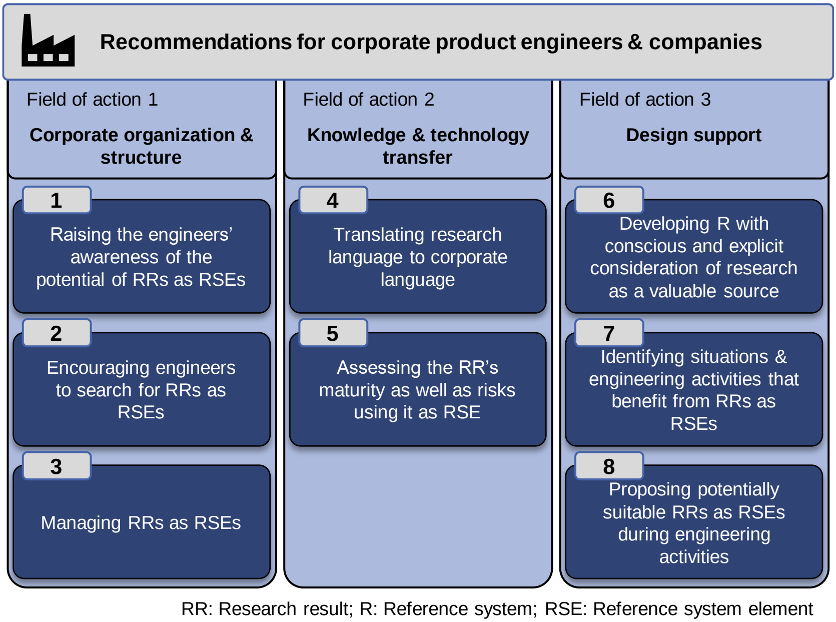


Figure 8.6: Overview of the eight recommendations for corporate product engineers and companies to improve their use of research results as reference system elements. Adapted from Kempf et al. (2025).

Important for this target group's recommendations, specifically, is to consider the effort-benefit ratio (Blessing & Chakrabarti, 2009). Therefore, the recommendations are stand-alone, and companies can first select the recommendations that offer the most potential to them. Furthermore, the companies themselves, or even better, accompanied by scientific support, must define how to implement the recommendations to fit their situation best. Finally, the recommendations do not intend to lead to many new tools or processes. Thus, companies should integrate the recommendations into their present toolset and processes whenever possible.

As multiple factors of the context and situation influence engineering projects, corporate engineering is highly diverse, even within one company (cf. Section 2.2). For example, the goals, requirements, and processes of advance engineering differ from those of serial engineering. While using research results as reference system elements is easier in the early phase of product engineering, research also offers valuable input for later activities. Only more strict boundary conditions or validation criteria might be applied. (VDI Verein Deutscher Ingenieure e.V., 2019a)

The following subsections present the fields of action and their recommendations.

8.2.1.1 Field of Action 1: Corporate Organization and Structure – Encouraging the Use of Research Results as Reference System Elements

The first field of action's recommendations address corporate organizations and their structure. These recommendations aim to improve the environment and encourage corporate product engineers to use research results as reference system elements.

Recommendation 1: Raising engineers' awareness of the potential of research results as reference system elements (possible inputs as a basis for the design/ engineering tasks)

> "Companies should regularly (e.g., quarterly) publish updates on the successful integration of technologies, process elements, knowledge elements, etc., from research into their (sub-)systems [e.g., products, services, product-service systems, processes] within the company. E.g., they can post success stories on the intranet or organize internal events. Here, they should include how the company benefited as well as the learnings of the colleagues involved. In addition, companies should share interesting research results with their engineers via regular updates. Even if the persons who identified the research results (e.g., through scouting activities) do not have an application yet, it may trigger another engineer." (Kempf et al., 2025, pp. 14–15)

Besides encouraging knowledge transfer and raising awareness of research results' potential as reference system elements, this recommendation offers the possibility to present successes to colleagues and management.

Here, it is essential to note that creating such updates is no trivial task. Companies might address multiple reader groups with the posts requiring different levels of detail in such updates. On the one hand, the company should inform a (probably relatively small) group of actually interested readers in a detailed manner to enable them to take up the ideas. On the other hand, the company could want to inform a second (probably large) group on a high level about success stories without bothering them with too much detail.

Recommendation 2: Encouraging engineers to search for research results as reference system elements (possible inputs as a basis for the design/ engineering tasks)

"Companies should encourage their engineers to look for research results that can serve as reference system elements. To make this possible, companies should

1. provide their product engineers with a dedicated budget and time to search for valuable and relevant research results. These resources give engineers the freedom to harvest research despite their daily work.

2. install an open-minded management with a scientific background that encourages the engineers to refer to research results in their engineering activities.

3. send their engineers to participate in (scientific) conferences to stay up to date on research developments. Furthermore, they should strengthen their networks; novel approaches can spark their association and creativity.

4. strengthen their collaboration with research facilities (e.g., by conducting collaborative workshops). Thereby, the transfer of concrete research results can be supported. Furthermore, the participating corporate engineers benefit from the researchers' influence and stay open-minded about the potential of research."

(Kempf et al., 2025, p. 15)

In addition to the first aspect of this recommendation, recommendation 8 addresses supporting engineers in searching for research results as reference system elements. Section 7.3 discusses different methods and approaches used in practice to search for and gather reference system elements in research.

Recommendation 3: Managing research results as reference system elements (possible inputs as a basis for the design/ engineering tasks)

"Companies should set up a research results management system to centrally coordinate the knowledge and associated information gathered from research. Therefore, the company should collect

1. research results already used within the company. These research results should be linked to the (sub-)systems [e.g., products, services, product-service systems, processes] they were the basis for or integrated into.

2. research results with potential that were identified but have not been implemented yet. Initial ideas or potential applications of the research results can be linked to these research results.

3. the research facilities/ researchers and involved partners that developed the research results and link them to the respective research results.

4. interesting research facilities/ researcher contacts even though they have not used their research results yet.

5. the contacts of the corporate engineers who identified and/ or used the research results and link them to the research results.

6. the in-house contact persons for different research facilities/ researchers and link them to the research facilities/ researchers.

7. the best practices and challenges of the involved product engineers and link them to the research results and/ or research facilities/ researchers."

(Kempf et al., 2025, pp. 15–16)

Knowledge management is an essential corporate activity in general (Albers, Reiss, Bursac, & Richter, 2016)[7]. Here, the focus is on managing knowledge related to

[7] Albers, Reiss, Bursac, and Richter (2016) included „manage knowlede“ as a basic activity of product engineering into the iPeM.

using research results as reference system elements. However, such a management system must be integrated into the general knowledge management system to support acceptance. The structure must meet the needs of all stakeholders. Engineering, production, business development, HR, etc., can all use reference system elements from research for their systems and processes.

8.2.1.2 Field of Action 2: Knowledge and Technology Transfer – Initial Steps Following the Identification of Research Results as Reference System Elements

The goal of the second field of action's recommendations is to support corporate engineers in the first steps after identifying potential reference system elements in research.

Recommendation 4: Translating research language to corporate language

> "The corporate engineers should translate the uncommon research-specific language used in the research result or its description into a language common to the company (e.g., by reformulating research questions as a description of the topic and goal of the research result). If not described already, corporate engineers should derive
>
> 1. the possible use cases and/ or applications of the research results.
>
> 2. an (initial) description of the expected benefits of using the research results in their (sub-)systems [e.g., product, service, product-service system, process]. Therefore, they should consider the benefit
>   a. for themselves (the company) as a provider of a (sub-)system by using the research result.
>   b. generated for customers of the (sub-)system when the research result is used in it.
>   c. for the users of the (sub-)system when the research result is used in it."
>
> (Kempf et al., 2025, p. 16)

Complementing this recommendation, the recommendations of field of action five encourage researchers to focus more on corporate needs. Recommendation 18 addresses the same issue from the funding agency's and (research) policymaker's point of view.

Recommendation 5: Assessing the research result's maturity as well as risks using it as a reference system element (possible inputs as a basis for the design/ engineering tasks)

"Corporate engineers should analyze the maturity and validity of the research result. For example, the Technology Readiness Levels (TRLs) concept can help to analyze the maturity. Furthermore, the corporate engineers should execute a risk assessment (e.g., using an FMEA or Gartner hype cycle) to identify possible risks of using the research result as input for their engineering activities. Finally, the corporate engineers should identify the next steps for using the research result in their engineering activities. Necessary steps can be, e.g., validation activities." (Kempf et al., 2025, p. 16)

While researchers can validate their results on a general level, each company is unique and has specific requirements. Thus, a company-specific assessment is essential for using research results as reference system elements.

8.2.1.3 Field of Action 3: Design Support – Supporting Corporate Engineers to Integrate Research Results as Reference System Elements in Their Engineering Activities

Field of action three's recommendations encourage design support (tools) for corporate product engineers that support them using reference system elements from research in their engineering activities. To develop these design supports, a close collaboration with research is necessary. Thus, the researchers' recommendations of the field of action six complement those of the field of action three.

Recommendation 6: Developing the reference system (collection of possible inputs as a basis for the design/ engineering tasks) with conscious and explicit consideration of research as a valuable source

"The design of the reference system is a complex and creative task that the engineers should consciously conduct throughout the entire development process of a new (sub-)system [e.g., product, service, product-service system, process] generation. Corporate engineers should be aware of this and specifically consider research as a valuable source for reference system elements." (Kempf et al., 2025, p. 17)

As shown in Chapter 5, synthesizing the reference system and its management is a highly complex task. This recommendation stresses integrating and considering research results as possible reference system elements as one aspect. The researchers' recommendation 16 complements this recommendation.

Recommendation 7: Identifying situations and engineering activities that benefit from research results as reference system elements (possible inputs as the basis for the design/ engineering tasks)

> "Corporate engineers/ companies should analyze their engineering activities to identify situations where using reference system elements from research could be beneficial. This analysis serves as the basis for the development/ implementation of design support, which makes corporate engineers look into research at the right moments. Including researchers in identifying such situations for scientific assistance will be beneficial (cf. Recommendation 14)." (Kempf et al., 2025, p. 17)

A smooth integration of searching for reference system elements in research in the right situations is vital to gaining acceptance. This recommendation provides the basis for this integration.

Recommendation 8: Proposing potentially suitable research results as reference system elements (possible inputs as the basis for the design /engineering tasks) during engineering activities

> "The company should implement a tool that suggests research results (e.g., stored and characterized according to Recommendation 3) as reference system elements on the fly during engineering activities. For example, this could be an AI tool that compares the present engineering activity with the characteristics of the research results. A prerequisite for this recommendation is to know about the relevant situations, as explained in Recommendation 7." (Kempf et al., 2025, p. 17)

The researchers' recommendation 15 complements this recommendation.

8.2.2 Recommendations for Researchers and Research Facilities to Improve Their Research Results' Usability as Reference System Elements in Corporate Product Engineering

Figure 8.7 provides an overview of the recommendations for researchers and research facilities to improve the usability of their research results as reference system elements in corporate product engineering. Additionally, the recommendations identify further research needs. Fields of action four to six include nine recommendations.

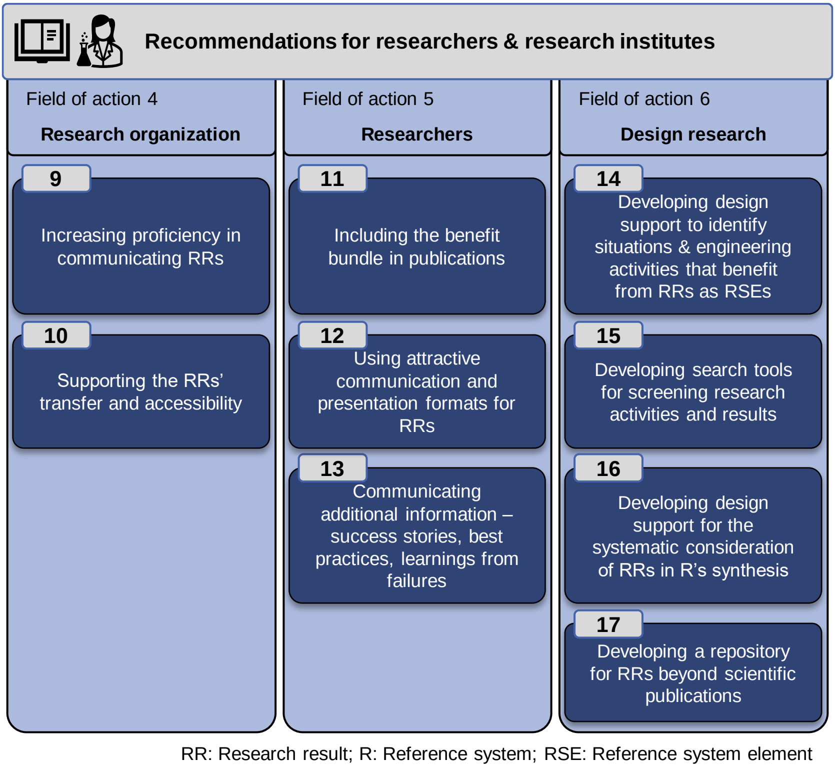


Figure 8.7: Overview of the nine recommendations for researchers and research facilities to improve their research results' usability as reference system elements in corporate product engineering. Adapted from Kempf et al. (2025).

Just as "every engineering process is unique and individual" (Albers, 2010, p. 4), this is valid for research projects, too. In that way, research facilities and researchers must define their personal ways of addressing the provided recommendations.

The following subsections present the fields of action and their recommendations.

8.2.2.1 Field of Action 4: Research Organization – Promoting Research Results and Supporting the Transfer

Field of action four's recommendations aim at research facilities to coach and support their researchers in transferring and communicating their research results. Of course, various facilities already support their researchers on this matter. However, that is not a standard yet.

Recommendation 9: Increasing proficiency in communicating research results

> "Research facilities should support the researchers in disseminating and promoting their results in up-to-date and attractive formats beyond text-based publications, e.g., short clips on the state of research. To this end, they should engage PR experts and develop a social media strategy. They should offer various options for presenting research results to address specific stakeholders' needs. Based on this strategy, the research facilities should offer coaching to the researchers. In addition, the research facilities can set up a presentation space. The presentation space offers researchers a professional environment to produce promotional and presentation material (e.g., photos, videos) or welcome interested industrial partners to present their results." (Kempf et al., 2025, p. 18)

Since researchers usually are not communication experts, PR experts help communicate the results professionally. Recommendation 19 supports this recommendation from the funding agency's and (research) policymakers' point of view.

Recommendation 10: Supporting the research results' transfer and accessibility

> "The research facility should provide a transfer-friendly environment by supporting spin-offs, patent strategies, etc.. Furthermore, research facilities should provide (long-term) repositories of research results. A well-structured overview and collection of research results will help interested parties to find them. In accordance, a well-described presentation of the research activities of the research facility also increases the findability of corresponding expertise." (Kempf et al., 2025, p. 18)

Different research facilities follow different strategic goals (cf. universities vs. Fraunhofer Society) (Czarnitzki & Licht, 2021). However, all should define their way on how to transfer their results. Recommendation 19 supports this recommendation from the funding agency's and (research) policymakers' point of view.

8.2.2.2 Field of Action 5: Researchers – Adjusting Research Results to the Customers (Corporate Engineers)

Field of action five's recommendations address researchers directly. These recommendations aim to support researchers in considering corporate needs when using research results.

Recommendation 11: Including the benefits bundle in publications

"Researchers should address the (expected) benefits bundle in their results (e.g., scientific publications). Here, researchers should describe the potential benefits for

1. the corporate engineers/ companies that use the research result as a reference system element in developing their (sub-)system [e.g., product, service, product-service system, process].
2. the customers of a (sub-)system when the research result is used in it.
3. users of a (sub-)system when the research result is used in it.

Additionally, the researchers should describe potential use cases or applications for their research results. Based on a risk assessment (e.g., SWOT) and description of the maturity (e.g., RRL, TRL), researchers should outline the next steps for using their research results in corporate engineering activities (cf. Recommendations 4, 5, and 18)." (Kempf et al., 2025, p. 19)

Researchers do not have detailed insights into all companies and want to produce results of general value that are not company-specific. Thus, the specified benefits bundle (cf. Section 2.1) will always be an expected bundle. Corporate engineers must translate the benefits for their specific situation as recommended in recommendation 4.

Research results do not always have to benefit corporate product engineering directly (e.g., considering the results of basic research projects). However, they can serve as a foundation for further research, ultimately benefiting corporate engineering. Thus, the benefits bundle still adds value to these results. Of course, the benefits bundle (cf. Section 2.1) also helps describe the research result's value for other target groups, such as fellow researchers.

Recommendation 12: Using attractive communication and presentation formats for research results

> "Researchers should adapt to the changing ways in which information is consumed. Thus, they should use social media and more visual (e.g., video, photo) ways of presenting and explaining their research results (cf. Recommendations 9 and 19). Additionally, the researchers should keep the language common in practice in mind (cf. Recommendation 4) and/ or provide a glossary." (Kempf et al., 2025, p. 19)

The research facilities must support the researchers in adapting to the changing ways of information consumption (cf. recommendation 9). Following this recommendation, video clips that are freely available present all 22 recommendations, too[8].

Recommendation 13: Communicating additional information – success stories, best practices, learnings from failures

> "In addition to presenting classical research results, researchers should communicate success stories and best practices for using their research results within corporate engineering activities. Besides the positive learnings, researchers should communicate failures and corresponding learnings within research as well as the transfer and use of research results in corporate engineering activities. To do so, cooperation with corporate partners is necessary and increases the validity of such learnings." (Kempf et al., 2025, p. 19)

Publications tend to have a positivity bias. Researchers usually only publish the results of successful experiments and studies. However, failures can lead to valuable learnings, too, and prevent other players from misinvestments.

8.2.2.3 Field of Action 6: Design Research – Developing Design Supports for Using Research Results as Reference System Elements in Corporate Product Engineering

The recommendations of the field of action six formulate research needs in developing design supports for using research results as reference system elements in corporate product engineering. A close collaboration of researchers with corporate product engineers is crucial for the success of these recommendations

[8] Cf. Kempf and Molz (2024)

(Blessing & Chakrabarti, 2009). Thus, the recommendations of the field of action three complement the recommendations of this field of action.

Recommendation 14: Developing design support to identify situations and engineering activities that benefit from research results as reference system elements (possible inputs as the basis for the design/ engineering tasks)

> "In cooperation with corporate product engineers, researchers should develop design support to identify the situations and engineering activities in product engineering that can benefit from considering research results. Such design support (e.g., a method or tool) can help raise awareness of the potential of research results and target efforts. In addition to general findings, such support needs to be specified for the individual companies, as it will depend on, e.g., the sector, the position in the value chain, and the position in the competition (cf. first mover vs. follower)." (Kempf et al., 2025, pp. 19–20)

Recommendation 14 corresponds to Recommendation 7 and serves as the foundation for Recommendations 8 and 16.

Recommendation 15: Developing search tools for screening research activities and results (beyond paper databases)

> "Researchers should develop support for corporate product engineers to search for research results systematically. Scientific databases for publications do allow systematic analysis. However, otherwise, the search for research results is mainly unsystematic (personal networks, conference participation, etc.). Methods and tools for searching for knowledge, technologies, etc., are rarely explicitly linked to research. Researchers could develop a "meta-crawler" harvesting different sources for research results." (Kempf et al., 2025, p. 20)

While the personal exchange of corporate and research experts is invaluable, it is resource-intensive. A support tool to crawl and link research results from different sources offers high potential.

Recommendation 16: Developing design support for the systematic consideration of research results in the reference system's synthesis (collection of possible inputs as the basis for the design/ engineering tasks)

> "Researchers should develop support for the systematic consideration of research results in the synthesis of the reference system. Here, the range spans from, e.g., making the reference system explicit and systematically modeling the reference system (e.g., using MBSE) to identifying and working with valuable research results. Creating a reference system is a complex and creative endeavor that generally has not yet received sufficient systematic support. That makes the process of synthesizing a reference system a research area that needs to be explored further." (Kempf et al., 2025, p. 20)

This recommendation corresponds to the companies' recommendation 6. Generally, an efficient reference system synthesis process constitutes more efficient product engineering processes. The specific consideration of research results adds another facet.

Recommendation 17: Developing a repository for research results beyond scientific publications

> "Researchers should develop a repository for researchers to share their research findings. Although the academic community effectively organizes and shares written research publications and data, other data formats, such as videos, digital models, and physical demonstrators, are not consistently archived and distributed across the research community. A repository can help to systematically complete the picture of research activities and results from research facilities and researchers." (Kempf et al., 2025, p. 20)

This recommendation aims not to provide project or proposal descriptions but to organize, archive, and offer any kind of research result. Besides developing such a repository, filling it out and tending to it are significant challenges. Thus, a sustainable operation concept is necessary.

8.2.3 Recommendations for Funding Agencies and (Research) Policymakers to Improve the Research Results' Usability as Reference System Elements in Corporate Product Engineering

Figure 8.8 provides an overview of the recommendations for funding agencies and (research) policymakers to improve the usability of research results as reference system elements in corporate product engineering. The fields of action seven and eight collect five recommendations.

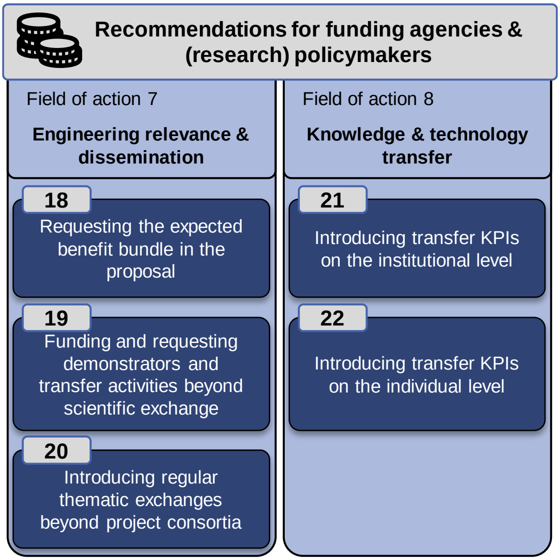


Figure 8.8: Overview of the five recommendations for funding agencies and (research) policymakers to improve the usability of research results as reference system elements in corporate product engineering. Adapted from Kempf et al. (2025).

The following subsections present the fields of action and their recommendations.

8.2.3.1 Field of Action 7: Engineering Relevance and Dissemination – Meeting the Industry's Needs

Field of action seven's recommendations aim at funding agencies and (research) policymakers to foster the usability and accessibility of research results.

Recommendation 18: Requesting the expected benefits bundle in the proposal

> "Funding agencies should consider the expected benefits bundle of the proposed research when selecting projects for funding. To do so, they should ask the applicants to describe the expected benefits of their research results. The applicants should
>
> 1. describe the benefits for the corporate engineers/ companies that use the research results as reference system elements in developing their (sub-)system [e.g., product, service, product-service system, process].
>
> 2. explain the potential benefits created for the customers of a (sub-)system when the research results are used in it.
>
> 3. outline the potential benefits created for users of a (sub-)system when the research results are used in it.
>
> In addition, the applicants should describe potential use cases or applications for their research results." (Kempf et al., 2025, p. 21)

The requirements of different funding programs vary greatly. Thus, the different entities follow different goals (e.g., funding agencies focused on basic research vs. collaborative industry-academia research projects). Research results do not always have to benefit corporate product engineering directly (e.g., considering the results of basic research projects). Thus, the described benefits bundles of such diverse research proposals will look completely different. However, they can serve as a foundation for further research. Since research funding aims to provide societal benefits, at least an initial, expected benefits bundle adds to the quality of research proposals and is valuable for proposal selection.

This recommendation complements recommendations 4 and 11.

Recommendation 19: Funding and requesting demonstrators and transfer activities beyond scientific exchange

"Funding agencies should request demonstrators to showcase the functionality of the research results and as a vehicle for transfer. The format of the demonstrators is highly dependent on the specific research project. Funding agencies should provide the necessary funding to enable the development of demonstrators. Furthermore, the demonstrators should be integrated into additional transfer activities (cf. Recommendations 9 and 10). As a result, funding agencies should request researchers to outline transfer activities in their project proposals beyond participation and publication in scientific conferences and journals. The active participation of researchers in standardization activities can be such a measure." (Kempf et al., 2025, p. 22)

Demonstrators are a crucial addition to scientific publications to transfer research results into corporate engineering. Research funding must also provide dedicated funding to enable and motivate researchers to develop demonstrators and engage in transfer activities with corporate stakeholders. The development of suitable demonstrators is a highly complex and individual process[9].

Recommendation 20: Introducing regular thematic exchanges beyond project consortia

"The funding agencies should support and organize regular thematic exchange meetings. Linking members of related project consortia and interested third parties can help to promote and further develop the research results and activities. This approach allows funding agencies to direct the audience and ensure the research results are disseminated within a local area, in addition to the usually global scientific conferences or journals. Partnering with, e.g., standardization organizations is beneficial to encourage productive meeting settings and goals. The format of the exchange meetings can vary (e.g., presentation vs. working sessions) and require thorough preparation and agenda to keep the stakeholders interested." (Kempf et al., 2025, p. 22)

Typically, researchers are more interested in international scientific publications. Thus, this recommendation is crucial to ensure regional or national dissemination.

[9]For example, Ref. 118: Wissenschaftskommunikation and Wissenschaftsjahre (2021) already anchors research communication as an essential part of research projects funded by the BMBF.

8.2.3.2 Field of Action 8: Research Incentives – Adjusting the Success Measurement of Research Projects

Field of action eight's recommendations aim at providing objective criteria and measures to funding agencies and (research) policymakers to monitor and motivate research facilities and individual researchers to stress their transfer activities. The panel experts see the use of KPIs (Key Performance Indicators) as highly controversial because it can encourage misuse. KPIs could motivate, e.g., researchers to adjust their research activities to optimize the KPIs only, neglecting the reasonableness of even higher KPIs. Therefore, funding agencies and research policymakers must pay special attention to this area if implemented and should only use it as an addition to other measures.

Recommendation 21: Introducing transfer KPIs on the institutional level

> “Funding agencies and research policymakers should increase the significance of transfer key performance indicators (KPIs) for research facilities. Focus should emphasize, e.g., spin-offs, patents, or companies participating in research projects.” (Kempf et al., 2025, p. 22)

Recommendation 22: Introducing transfer KPIs on the individual level

> “Funding agencies and research policymakers should increase the significance of transfer key performance indicators (KPIs) for researchers. Focus should emphasize, e.g., patents, standards, open access publications, companies involved in research projects, and transfers of research results to companies.” (Kempf et al., 2025, p. 22)

While recommendation 21 addresses KPIs on the institutional level (e.g., universities or individual research groups), recommendation 22 addresses individual researchers. The core KPIs for research so far are, i.a., publication numbers and citations. Besides requesting specific publication numbers per research project, funding agencies and (research) policymakers can also use transfer KPIs to request more transfer activities.

8.3 Conclusion

In Chapter 8, this thesis developed 22 recommendations to improve research results’ usability as reference system elements in corporate product engineering. Thus, this chapter answered the following research and sub-research questions:

RQ4. What are suitable recommendations to improve the usability of research results as reference system elements in corporate product engineering?

RQ4.1. How can corporate product engineers be motivated for and supported in searching for and applying RSEs from research?

RQ4.2. How can researchers be motivated and supported to increase the usability of their research results as RSEs in corporate product engineering projects?

RQ4.3. How can funding agencies/ policymakers positively influence the usability of research results as RSEs in corporate product engineering projects?

This thesis used a multi-method approach highlighting the sounding board method to answer the research questions and to evaluate the results initially. Figure 8.9 summarizes the research approach and the core results of Chapter 8.

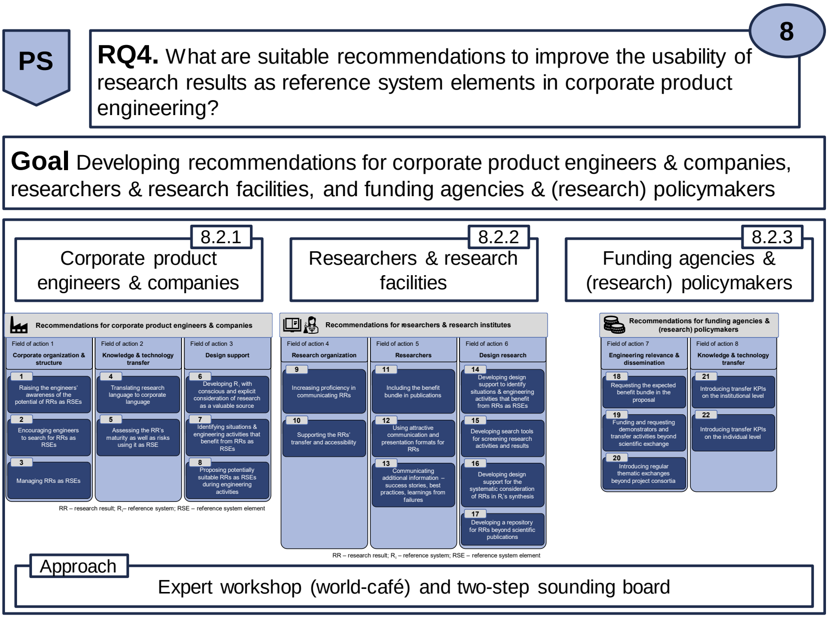


Figure 8.9: Summary of the objectives, approach, and results of the Prescriptive Study developing recommendations to improve the research results' usability as reference system elements. The results are illustrated using icons and presented in detail in Figure 8.6, Figure 8.7, and Figure 8.8.

This study used a world-café approach with 43 experts to deduce measures to overcome the challenges and barriers of using research results as reference system elements in corporate product engineering according to Kempf, Thapak, et al. (2023) (cf. Section 7.4). Complemented by the analysis of the previously generated results regarding the reference system's fundamentals (cf. Chapter 5), classification of research results (cf. Chapter 6), and the current practice of using research results as reference system elements in corporate product engineering (cf. Chapter 7) this chapter developed the recommendations. Consecutively, this study used the sounding board method to evolve the recommendations in two iterations. These recommendations aim to improve the usability of research results as reference system elements in corporate product engineering. Therefore, this chapter provides 22 recommendations clustered in eight fields of action, addressing three target groups:

- The recommendations of *fields of action one, two, and three* aim at supporting *companies and corporate product engineers* in using research results as reference system elements within their engineering activities.
- The recommendations of fields of action four, five, and six aim at supporting *research facilities and individual researchers* to increase the usability of their research results as reference system elements within corporate product engineering.
- The recommendations of fields of action seven and eight aim at supporting *funding agencies and (research) policymakers* in motivating and supporting research facilities and researchers to increase the usability of research results as reference system elements within corporate product engineering.

Following one of the recommendations (Recommendation 12), video clips[10] present all fields of action and their recommendations in an up-to-date format.

Since all research projects and funding programs are as unique and individual as "every engineering process is unique and individual" (Albers, 2010, p. 4), users of these recommendations must consider their individual situation to develop the recommendations' implementation strategies. Corporate users and users of funding agencies and (research) policymakers benefit from partnering with research partners.

These 22 recommendations help lower the challenges and barriers to using research results as reference system elements in corporate product engineering. Overcoming these barriers is essential in transferring knowledge and technology from research into corporate product engineering. Therefore, companies can evolve their offers to society and increase their competitiveness.

This thesis also chose the sounding board approach to evaluate the recommendations initially. A holistic application and success evaluation of the recommendations, as in the second Descriptive Study of Blessing and Chakrabarti (2009), was not feasible within this thesis' timeframe. However, the second sounding board's expertise ensures the recommendation's principal applicability, and the board's relevance evaluation indicates the effectiveness of the final 22 recommendations once implemented. Since this thesis developed the recommendations by analyzing the German situation (cf. Chapter 7) and using German experts as the sounding board, it cannot generalize them to international

[10] Cf. Kempf and Molz (2024)

contexts. Due to the German system's complexity and the sounding board's international expertise, a transfer to other settings stands to reason.

9 Summary and Overall Conclusion

The development of new systems is always based on references. Therefore, the collection of these references – the synthesis of the reference system – plays a major role in product engineering. Methodical support is necessary to identify and collect suitable references and model them within the reference system to leverage the potential within the synthesis of the reference system. Analyzing the existing approaches in the current state of research (cf. Chapter 2), the model of SGE promises excellent potential as a basis for developing such methodological support in synthesizing the reference system. Based on the stage of development of the model of SGE – System Generation Engineering, this thesis derived the following overarching research goal (cf. Chapter 3):

> The overarching research goal this thesis contributes to is the establishment of RSM – Reference System Management as a core aspect of product engineering to improve the development of successful products.

RSM – Reference System Management describes the initial and continuous synthesis and analysis of a reference system. It organizes the interaction between the engineering team and the reference system. The goal of the activities of reference system management is to provide a well-suited reference system efficiently.

The first descriptive investigations regarding the overarching research goal deemed it necessary for a further focus of this thesis. As explained in Chapters 3 and 5, this thesis chose the field of research as an exemplary source of potential reference system elements for corporate product engineers to explore and develop RSM. Research produces cutting-edge knowledge and technologies, and their implementation in corporate systems is vital to overcoming the current challenges that societies face, such as climate- and energy-related issues (EFI – Commission of Experts for Research and Innovation, 2022; Frank et al., 2007; Kleiner-Schaefer & Schaefer, 2022; Maresova et al., 2019; Mazurkiewicz & Poteralska, 2017). Thus, starting from the overarching research goal, this thesis narrowed down the research objective as follows:

> This thesis aims to develop the field of research results as possible usable reference system elements for corporate product engineering as one core aspect of RSM – Reference System Management.

Four research questions operationalize the research objective and give this thesis a structure:

RQ1. What are the fundamentals of the reference system within the model of SGE – System Generation Engineering?

RQ2. How can research results be classified to facilitate their exploration as reference system elements in corporate product engineering projects?

RQ3. How do corporate product engineers search for and apply reference system elements from research, and what challenges do they face in this process?

RQ4. What are suitable recommendations to improve the usability of research results as reference system elements in corporate product engineering?

The Design Research Methodology (DRM), according to Blessing and Chakrabarti (2009), structures this thesis to address the research objective and answer the research questions systematically. Thus, this thesis passes through the research stages of Descriptive Study I, Prescriptive Study, and Descriptive Study II, as described in Chapter 4. The IRTG 2078 provides an excellent research environment for this thesis to conduct the research, as the IRTG addresses the aforementioned societal challenges by holistically researching the lightweight material system CoDiCoFRP (Continuous-DisContinuous long Fiber Reinforced Polymer). Therefore, the IRTG integrates various engineering research disciplines and produces a wide variety of research results.

Before addressing the narrowed research objective of this thesis, the first research question addresses the overarching research goal to set the basis of RSM – Reference System Management. Therefore, this thesis conducts three studies as the **first part of the Descriptive Study I** researching the fundamentals of the reference system (cf. Chapter 5).

The first study results in 20 factors from the engineering context and situation that can influence the synthesis of the reference system and its elements (cf. Section 5.1). The study categorizes these factors into four clusters: *Team/ people*, *system*, *organization*, and *(macro-)economy*.

The influencing factors impact each other and, as a system, serve as indicators for what (types of) elements the reference system should contain. Understanding the influencing factors and their interplay serves as valuable input when developing design support for synthesizing the reference system.

The second study identifies 12 knowledge spaces as sources for potential reference system elements and 30 methods and tools that product engineers can use to search for and apply reference system elements from these sources (cf. Section 5.2). The methods and tools fall into five categories:

- Creativity methods
- Data analysis methods
- Market and competition analysis methods
- Similarity methods
- Trend analysis methods

These methods and tools enable searching for and applying reference system elements from the sources *same branch*, *other branch*, *research*, and *society and nature*. The accessibility of the elements within the sources divides each source into three subspaces (part of corporate knowledge, no part of corporate knowledge but accessible to the engineering team, and existing but not accessible to the engineering team). The study introduces the Reference System Element Identification Atlas to summarize all findings (cf. Figure 5.9). This study confirms the conclusion of the state of the research that references are an essential part of many methods in product engineering. However, the relations and role of references in these methods are implicit in most cases.

Both studies illustrate the complexity of the synthesis of a well-suited reference system. A complex system of multiple factors that vary over time influences the reference system and its elements. Various unique sources exist for potential reference system elements, and many methods and tools can support searching for and applying reference system elements. However, adjustments are necessary to fill the reference system with elements systematically and explicitly. The complexity of the influencing factors and the variety of the sources constitute focusing on the field of research as a source of potential reference systems for corporate product engineering in this thesis.

The third study introduces three distinct subsystems of the reference system to define its internal structure based on the system triple of product engineering (cf. Section 5.3). Figure 9.1 illustrates the relations of the three subsystems of the reference system to the system triple of product engineering of the according product development project.

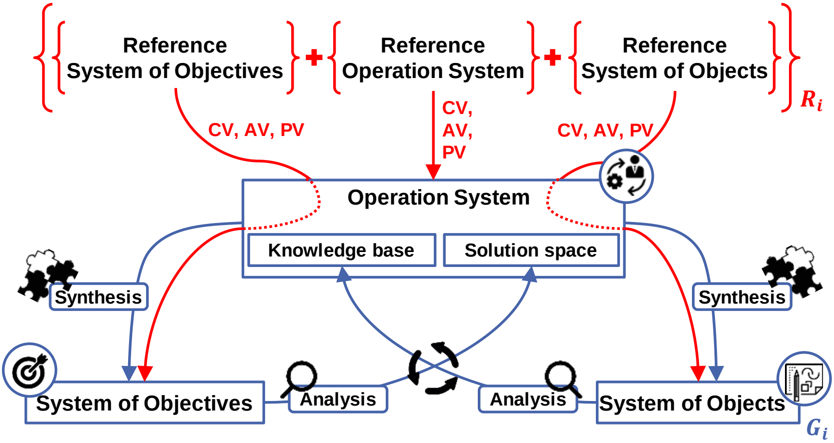


Figure 9.1: The reference system's internal structure. Three subsystems define the internal structure based on the system triple of product engineering. Adapted from Albers, Kempf, et al. (2024).

The reference system of objectives contains all reference system elements that form the basis to develop the system of objectives of the according product development project. Respectively, the reference operation system and reference system of objects contain all elements that form the bases for the operation system and system of objects of the according product development project.

Defining the reference system's internal structure is the first step in developing model-based approaches to model the reference system. Therefore, this study provides the foundations for developing new Advanced Engineering approaches that leverage the potentials of cross-generation engineering based on the model of SGE – System Generation Engineering.

In conclusion, these results regarding the fundamentals of the reference system introduce the concept of RSM – Reference System Management to the state of research. The thesis systematically identifies and analyzes the factors influencing the reference system and its elements, provides a comprehensive assessment of possible sources for reference system elements and a collection of methods and approaches to harvest these sources, and defines the inner structure of the reference system. This thesis lays the foundation for research activities to operationalize reference system management and, consequently, system generation engineering by adding these results to the state of research.

After researching the fundamentals of the reference system in the first research question, this thesis focuses on the research objective starting from the second research question. The research objective is to develop the field of research results as potential reference system elements for corporate product engineering as one core aspect of RSM – Reference System Management. Addressing the different types of results that research produces and the current role of reference system elements from research, including the accompanying challenges in searching and applying these elements, research questions two and three cover the **second part of the first Descriptive Study**. This study conducted one study each to answer research questions two and three.

The first study identifies five clusters of research results types. The clusters *publications*, *prototypes*, *equipment*, *data*, and *experience* contain 33 types of research results. Subsequently, this study develops nine research readiness levels based on the technology readiness levels to introduce an initial classification model for research results of different degrees of maturity (cf. Chapter 6). The classification model forms the theoretical basis for the field of research results as reference system elements in corporate product engineering.

The second study concludes the first Descriptive Study by researching the current situation of corporate product engineers using reference system elements from research in their engineering activities (cf. Chapter 7). Therefore, the study elucidates three aspects:

- Reasons and triggers to use reference system elements from research in corporate product engineering
- Methods and approaches for product engineers to search for and apply reference system elements in research
- Challenges and barriers product engineers face in searching for and applying reference system elements from research

Reasons are arguments of a more general nature that favor using research results as reference system elements in corporate product engineering. Seven clusters categorize the reasons for using research results as reference system elements:

- Research offers *reliable sparring partners*
- Partners from research enable *open communication*
- Partners from research have *high qualification*
- Research offers *high-quality reference system elements*

- Reference system elements from research offer *competitive advantage and mastering complexity*
- Using reference system elements from research holds *cost and time efficiency*
- Using reference system elements from research benefits the product's and company's *marketing and image*

Triggers, on the other hand, are the events/ concrete circumstances that initiate searching for or applying reference system elements from research.

The reasons and triggers complement and specify the general factors from the engineering situation and context that influence the reference system. Therefore, the reasons and triggers are valuable input for developing methodical support for searching and applying reference system elements from research.

The study revealed 15 methods and approaches product engineers use in practice to search for and apply reference system elements from research. These methods and approaches range from chance-based to highly structured, and from independent to highly collaborative. Four of the identified methods and approaches relate to the search for reference system elements in research. Five other methods and approaches focus on applying the reference system elements identified in research to the reference system. Finally, the last six methods and approaches support both searching for and applying reference system elements from research. Some methods and approaches qualify to address all clusters of research results, but not all of them do.

Comparing the identified 15 methods and approaches with the Reference System Identification Atlas and its 30 methods and tools indicates that the search and application process holds potential for improvement. However, as discussed before, the methods and tools in the atlas need adjustment for being used to identify elements for the reference system explicitly (cf. Section 5.2) and for being applied to the source research (cf. Chapter 7).

Finally, Figure 9.2 illustrates the challenges and barriers that product engineers face in searching for and applying reference system elements from research.

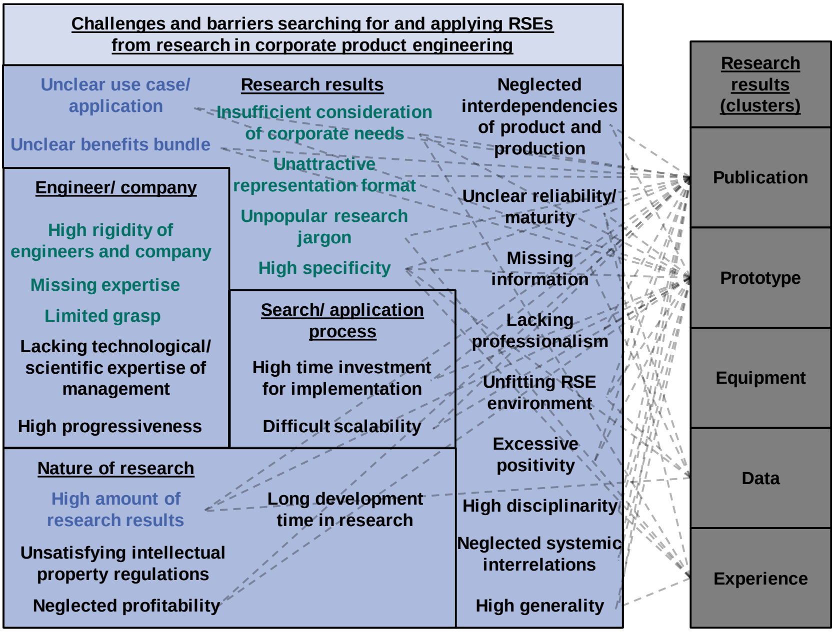


Figure 9.2: 26 potential challenges and barriers that can hinder product engineers in searching for and applying different research result types as reference system elements. Adapted from Kempf, Thapak, et al. (2023).

Out of 26 challenges and barriers, three specifically hinder the search for reference system elements in research, 16 impede the application of reference system elements from research into the reference system, and seven challenges and barriers exacerbate both the search for and the application of reference system elements from research. The challenges and barriers relate to the *research results*, the *product engineer or the company*, the *nature of research*, or the *search or application process*.

In conclusion, the findings regarding research results as reference system elements analyze the diverse state of research, discussing the classification of research results. This thesis systematically identifies and analyzes, on the one hand, the triggers and reasons for corporate product engineers to use and, on the other hand, the challenges and barriers the engineers face when searching research results as input for their engineering tasks. Thus, besides the further research activities within this thesis, this thesis sets the basis for further research on specific design support for corporate product engineers by adding these findings to the state of research.

The recommendations developed to answer the fourth research question within the **Prescriptive Study** aim to address the identified challenges and barriers by improving the usability of research results as reference system elements in corporate product engineering (cf. Chapter 8). Based on the findings from answering the previous research questions, this thesis identified three target groups for the recommendations:

- Corporate product engineers and companies, since they are the recipients and direct users of the reference system elements from research
- Researchers and research facilities, since they are the donors and creators of the research results as potential reference system elements
- Funding agencies and (research) policymakers, since they shape the overarching framework enabling the transfer of research results as reference system elements

Figure 9.3 presents the overview of the eight recommendations in three fields of action for corporate product engineers and companies to support them using research results as reference system elements in their product engineering activities (cf. Subsection 8.2.1).

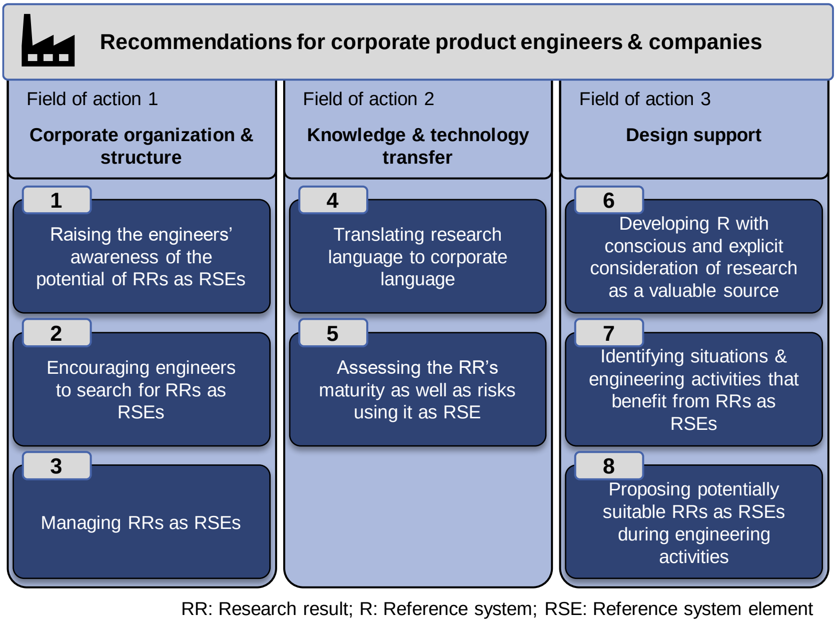


Figure 9.3: Eight recommendations in three fields of action address corporate product engineers and companies to support them using research results as reference system elements. Adapted from Kempf et al. (2025).

The recommendations of the first field of action focus on corporate organizations and their structure, aiming to create an environment that encourages product engineers to utilize research results as reference system elements. The second field of action provides recommendations to assist corporate engineers in the initial steps after identifying potential reference system elements from research. The third field of action emphasizes the need for design support tools to help corporate product engineers incorporate reference system elements from research into their engineering activities. Developing these design support tools requires close collaboration with researchers, making the recommendations of the sixth field of action a vital complement to those of the third field.

Figure 9.4 presents the overview of the nine recommendations in three fields of action for researchers and research facilities to improve research results' usability as reference system elements in corporate product engineering (cf. Subsection 8.2.2).

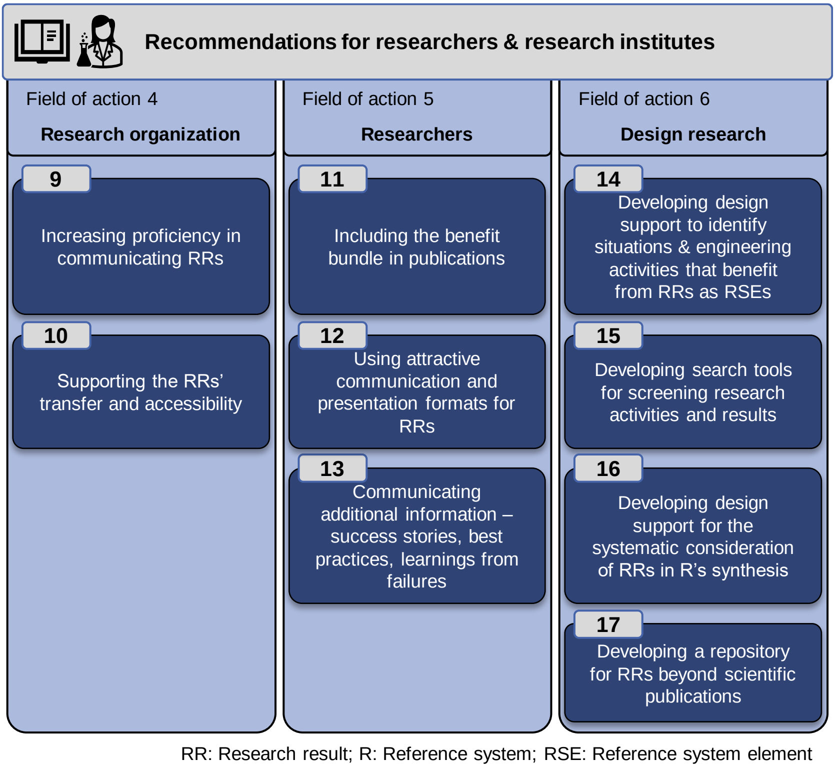


Figure 9.4: Nine recommendations in three fields of action address researchers and research facilities to improve research results' usability as reference system elements in corporate product engineering. Adapted from Kempf et al. (2025).

The recommendations in the fourth field of action are directed at research facilities, aiming to coach and support their researchers in effectively transferring and communicating their research results. While some facilities already provide such support, it is not yet a standard. The fifth field of action addresses researchers directly, encouraging them to consider corporate needs when communicating and publishing their research results. The sixth field of action outlines the research needs for developing design support tools that help incorporate research results as reference system elements in corporate product engineering. Close collaboration between researchers and corporate product engineers is essential for these recommendations to succeed, making the recommendations of the third field of action a vital complement to those in the sixth field.

Figure 9.5 presents the overview of the five recommendations in two fields of action for funding agencies and (research) policymakers to improve research results' usability as reference system elements in corporate product engineering (cf. Subsection 8.2.3).

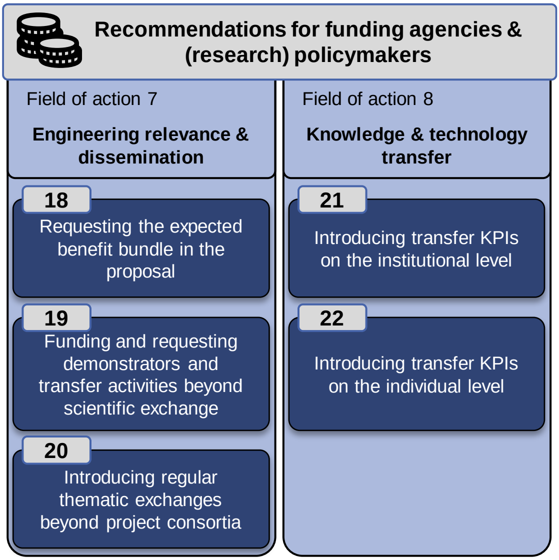


Figure 9.5: Five recommendations in two fields of action address funding agencies and (research) policymakers to improve research results' usability as reference system elements in corporate product engineering. Adapted from Kempf et al. (2025).

The seventh field of action provides recommendations for funding agencies and (research) policymakers to enhance the usability and accessibility of research results. The eighth field of action offers objective criteria and measures for funding agencies and (research) policymakers to monitor and motivate research facilities and individual researchers to prioritize their transfer activities.

In conclusion, the results leading to the 22 recommendations for corporate product engineers and companies, researchers and research facilities, and funding agencies and (research) policymakers add a scientifically sound assessment of the most significant levers to improve research results' usability as reference system elements in corporate product engineering to the state of research. This thesis lays the groundwork for further research regarding the support of technology and knowledge transfer from research to corporate product engineering. Furthermore, it provides the possibility to prioritize research and engineering efforts.

The study's design to develop the recommendations for the three target groups also ensures an initial evaluation of the recommendations covering an **initial second Descriptive Study**. Thus, after eliminating two recommendations, 22 relevant recommendations remain to improve the usability of research results as reference system elements in corporate product engineering and applicable in principle.

In summary, this thesis introduces RSM – Reference System Management to the model of SGE – System Generation Engineering by researching and explaining the fundamentals of the reference system. It develops the field of research results as potential reference system elements within reference system management. Consequently, the findings extend the KaSPro's methodological framework, enabling design research related to the initial and continuous development of the reference system with a particular focus on utilizing research results. Therefore, this thesis makes a theoretical and practical contribution toward overcoming current societal challenges by enhancing the usability of research results as references for corporate product engineering.

10 Outlook

The findings and results of this thesis form starting points for further research. The following sections categorize potential further research into two areas. Section 10.1 covers research aimed at further improving the integration of references from research into corporate product engineering. Section 10.2 describes further research advancing system generation engineering based on the reference system.

10.1 References From Research in Reference System Management

Some of the recommendations outlined in this thesis directly highlight further research needs to improve the usability of research results as reference system elements in corporate product engineering.

This thesis identifies a need for design support to assist corporate product engineers in searching for references within research. First, such design support must help product engineers recognize engineering situations that can benefit from references from research. Second, it should guide them methodically in selecting the appropriate methods or approaches for searching and applying these references within their engineering activities.

While this thesis has focused on research as a valuable source for references, the next step should be to broaden this design support to encompass all potential sources of reference system elements. Consequently, the design support should aid product engineers in selecting the most promising sources for searching reference system elements and provide methodical assistance in acquiring and applying suitable references through appropriate methods and approaches according to the engineering context and situation.

Leveraging the potential of AI, further research could focus on developing automated design support to suggest potentially suitable references from various sources to the product engineers in their engineering activities on the fly.

This thesis lays the groundwork for such future research through its investigation of the general influencing factors on the reference system resulting from the engineering context and situation (cf. Section 5.1), as well as specific reasons and triggers for using references from research (cf. Section 7.2). The Reference System Element Identification Atlas (cf. Section 5.2) and the methods and approaches for searching for and applying references from research used in practice (cf. Section 7.3) provide a starting point for selecting appropriate methods or approaches.

While this thesis did not focus specifically on direct industry-academia collaboration projects for knowledge and technology transfer, it set the basis for two ongoing EU-funded projects centered on this type of collaboration. The INDUSAC[1] project develops a methodology to match corporate engineers who bring engineering challenges with researchers and students solving these challenges (cf. Bastian et al., 2024; Kempf, Hellwig, et al., 2023 and Hellwig, 2023[2]). The EU.FFICIENT[3] project aims to train facilitators to manage and facilitate collaboration projects between researchers and corporate engineers or public and societal entities, with a special focus on utilizing research results and knowledge.

10.2 The Reference System in Advanced Systems Engineering

Further research activities focus on advancing system generation engineering in various aspects.

Model-based Advanced Engineering approaches are essential for managing and mastering the complexity of the simultaneous development of multiple variants of a system in development and multiple system generations. This thesis provides the basis for modeling the reference system (cf. Section 5.3). The Collaborative Research Center (CRC) Convide - Consistency in the View-Based Development of Cyber-Physical Systems[4] conducts basic research on maintaining consistency across multiple simultaneous interlinked product engineering projects and collaborating engineering disciplines using model-based approaches. One core aspect is the role and consistency of the respective reference systems.

[1] Funded by the European Union’s Horizon Europe Programme under grant agreement No 101070297 – https://indusac.eu/
[2] Student thesis (unpublished)
[3] Funded by the European Union’s Horizon Europe Programme under grant agreement No 101135297 – https://eufficient.eu/
[4] German: SFB – Sonderforschungsbereich 1608; funded by the DFG – https://www.sfb1608.kit.edu/

Consequently, this CRC develops the foundations and first approaches for model-based cross-generation engineering as Advanced Engineering approaches.

Sustainability is currently omnipresent in product engineering and public discourse due to the societal challenges linked to climate change and energy consumption. Here, further research is needed to leverage the potential of the model of SGE explicitly. Albers, Tusch, et al. (2024) have already demonstrated the connectivity of the model of SGE to sustainability strategies. This contribution elucidates the potential of researching and addressing circularity in product engineering using the model of SGE. The CRC Circular Factory[5] builds on this understanding to research approaches for the “perpetual product”, integrating linear and circular product engineering strategies. The CRC conducts basic research to understand and establish engineering approaches based on the model of SGE and the reference system in particular.

These two CRCs are but two prominent examples of further research activities in which the reference system and reference system management are essential. Additional research activities are exploring, e.g., upgradability as the continuous modification of systems in operation (cf., e.g., Albers et al., 2023) or the future-robust development of product portfolios (cf., e.g., Schlegel, Just, et al., 2024; Schlegel, Pommerer, et al., 2024) and the implications for the reference systems of according systems.

[5] SFB 1574 – Kreislauffabrik; funded by the DFG – https://www.sfb1574.kit.edu/

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Appendix A

Composition of the Participants of the Study to Verify the Research Need

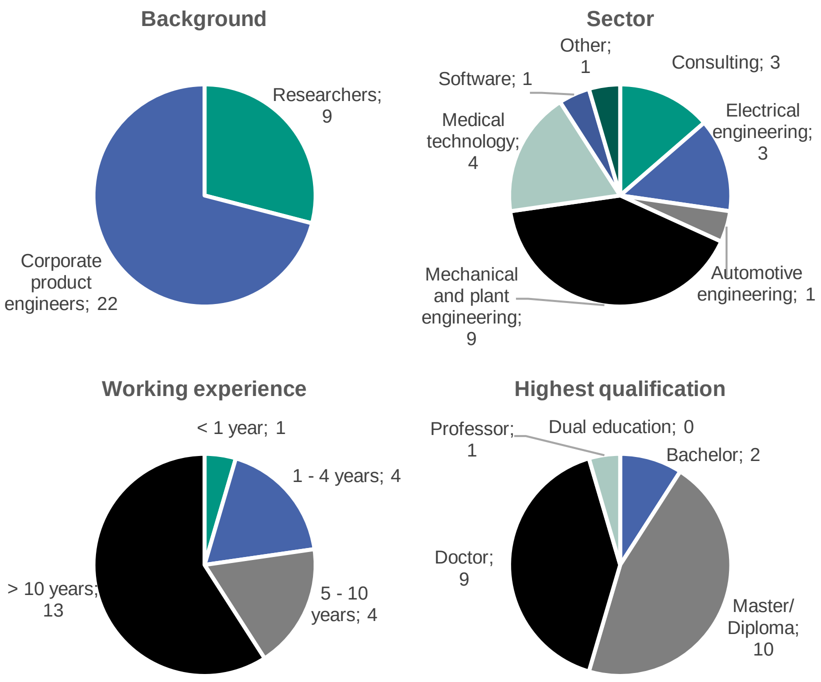

Figure A.1: Composition of the participants of the study to verify the research need based on Kempf, Rapp, and Albers (2022).

Appendix B

Description of the Factors Influencing the Reference System and its Elements

Table B.1: Short descriptions of the identified influencing factors on the reference system. Based on Kempf, Sanke, et al. (2022) and Sanke (2021)[1].

Influencing factor	Values	Influenced characteristic
Experience of engineer	Low – high	Homogeneity of team
		Type of RSE_i**
		Level of detail of RSE_i**
Homogeneity of team	Homomogeneous – heterogeneous	Homogeneity of R_i*
Origin of engineer	E.g., discipline, external/ internal, …	Homogeneity of team
		Origin of RSE_i**
		Terminology of R_i*
Activities of product engineering	c.f. Subsection 2.2.2	Type of RSE_i**
Development time	Short – long	Origin of RSE_i**
Number of cooperating companies	Few – many	Homogeneity of R_i*
		Homogeneity of team
Number of variants	Few – many	Structure of the system architecture
Origin of RSE_i**	E.g., internal/ external, cf. Section 5.2	Type of RSE_i**
System generation	$G_i \text{ with } i \in \mathbb{N}.$	Homogeneity of R_i*
		Level of detail of RSE_i**
		Origin of RSE_i**
Product lifecycle duration	Short – long	Origin of RSE_i**
Production volume	Batch – mass production	Standardization level of components
Structure of the system architecture	E.g., modular	Origin of RSE_i**
		Standardization level of components
Product variety	Low – high	Structure of the system architecture
Standardization level of components	Low – high	Level of detail of RSE_i**
		Maturity level of RSE_i**

[1] Student thesis (unpublished)

Type of company	E.g., start-up, OEM, SME, …	Experience of engineer
		Number of cooperating companies
		Number of variants
		Origin of engineer
Corporate partnership	E.g., joint venture, industry-academia collaboration, …	Number of cooperating companies
Industry	E.g., automotive, machinery, software engineering, …	Legal situation
		Market uncertainty
		Product lifecycle duration
		Standardization level of components
		Structure of the system architecture
Legal situation	E.g., stable/unstable, secure/ insecure	Origin of engineer
		Structure of the system architecture
Market uncertainty	Low – high	Development time
		Structure of the system architecture
Protection status	E.g., patented, open-access publication, …	Approval for use of RSE_i**

*Characteristic of reference system R_i
**Characteristic of reference system elements RSE_i

Appendix C

Methods and Tools to Harvest Different Knowledge Sources

Table C.1 Description of methods and tools to harvest different sources for reference system elements. Adapted from Kempf, Rapp, et al. (2023) and Derst (2021)[1].

Method/ tool	Description	Source harvested	Exemplary RSE types
Brainstorming	Ideas from a group of participants on a particular topic are collected uncommented and unstructured. Stimulating memory and associating ideas in the current context is the basis of brainstorming	Creativity/ experience	E.g., product data, process data
Delphi method	In this method, experts are selected and then interviewed in written form. In the first round, they are asked for starting points for solving a problem. Based on the combined list of starting points, they are asked to make further suggestions in round two. Lastly, they are asked to identify the most valuable suggestions from rounds one and two	Creativity/ experience	E.g., product data, process data
InnoBandit	Megatrends, microtrends, and reference products are offered to foster creative impulses in problem-solving during product engineering.	Creativity/ experience	E.g., product data, process data
Lateral thinking	This method is about restructuring and provoking new patterns. Based on “outside, unplanned stimuli to provide events that do not follow the natural sequence of development of an idea,” new solutions are created.	Creativity/ experience	E.g., product data, process data

[1] Student thesis (unpublished)

Method 635	Based on Brainstorming. In this method, six participants write down three ideas. The ideas are then passed on five times and supplemented.	Creativity/ experience	E.g., product data, process data
Random picture technique	In a limited time, abstract ideas are collected through participants' creativity. Creativity is encouraged by randomly selected images not related to the topic.	Creativity/ experience	E.g., product data, process data
Synectic	After an introduction to a problem, familiar assumptions are rejected. References are drawn from other spheres to start analogies.	Creativity/ experience	E.g., product data, process data
TILMAG	The ideal properties of a system are formulated. These properties are abstracted and transferred to another field. In the other field, elements that fulfill these properties are identified. These elements are the basis for solving the original task.	Creativity/ experience	E.g., product data, process data
TRIZ - method	“Theory of Inventive Problem Solving”, in which a problem is analyzed and then abstracted into a standard problem. A standard solution is derived with the help of various tools, such as ARIS. This is concretized into a unique solution.	Standard solution principles	E.g., standard solutions and problems
Data mining/ KDD	Data is analyzed, patterns in data are identified, and connected knowledge can be gained.	Internal/ accessible database	E.g., product data, process data
Design catalogs	This tool offers a summary of existing and proven solutions for particular construction tasks. These catalogs show objects as a line sketch, equation or drawing, or illustration, and additionally, their respective properties.	Design catalogs	Construction data
Literature search	Used to find important information about the current state of research and state of art. The method provides an important overview of existing solutions.	E.g., libraries, patent offices, standardization organizations	E.g., literature from research, product data, guidelines, processes, patents, standards
Patent analysis	Analysis of patent databases for valuable patents. Various approaches are available to support the analysis, e.g., an	Patent database	Patents

	automated classification procedure.		
Process mining	Extract data on development processes from past product development projects. Identified knowledge patterns can be used to uncover good practices and lessons learned.	Internal/ accessible database	Process (elements)
A2MAC1	Platform reengineering vehicles of all brands (reverse engineering) and offering scans and data of the subsystems and parts.	A2MAC1 database	Data on competing products, e.g., scans or images
Benchmarking	Systematic comparison of own products or processes with other companies. Thus, best practices are identified. These can be used to improve products and processes.	Competitors/ market	Product data, solution principles
Competitive intelligence	Identification of competitive knowledge. In the first step, information needs are identified with the help of corporate intelligence audits. Subsequently, the raw data is collected, evaluated, and analyzed. In the final step, the results are processed, presented, and used	Competitors	E.g., competitor products
Competitor analysis	Comparison of the capabilities of direct, potential, and indirect competitors. Mainly on an economic and portfolio level. The goal is to identify the companies' strengths, weaknesses, and strategic development. One aspect is the fulfillment of customer needs.	Competitors	Competitive products and processes
Cross industry innovation	Based on analogical thinking, cross-industry innovation uses successful solutions from other industries (outside-in).	Competitors/ market	E.g., technologies, patents, business models, and processes
Head hunting	Targeted recruitment of experts from competitors' employees or other market participants, for example, with the help of a head hunter.	Competitors/ market/ research	Expert/Expert knowledge from previous projects
Joint-venture (co-operation)	Two or more companies join to form a joint legal organization. This allows companies to access and use certain parts of the cooperating company, such as products and processes, as a reference. Other forms of cooperation can range from	Competitors/ market	E.g., product and process data of the competitor/ market participant

	"occasional information" to "fusion" of companies. This enables the usage of knowledge elements of the cooperating companies to various extents.		
Market analysis/ environment analysis	The market is considered. The different characteristics of the business environment are evaluated, and conclusions are drawn. The market analysis can be divided into a situation analysis and a market observation	Market	E.g., technological trends, market products
Product reverse engineering	A method for acquiring knowledge from competitors' products and machines. Competition products are tested, broken down into their subsystems and components, and then analyzed. Subsequently, knowledge about materials, manufacturing processes, etc., can be gained.	Competitors	E.g., competitor products
Technology portfolio	Assessment of technological potential. The evaluation is based on a comparison of technology attractiveness to the resource strength of a company. Technology attractiveness and resource strength are plotted on a two-dimensional matrix. This can then be used to recommend different technologies for pre-prioritization	Competitors/ market/ research	New technologies
Technology scouting	Early identification of developments in science and technology relying on formal and informal sources. "[Characteristics of a scout] include being a lateral thinker, knowledgeable in science and technology, respected inside the company, cross-disciplinary orientated, and imaginative."	Competitors/ market/research	New technologies
Analogies	Identifying possible analogies to solve problems based on already existing technical or non-technical systems	Internal/accessible database/ creativity/experience	E.g., physical effects, structural data, process data
Bionic	Solutions and principles of biology are investigated. Identified solutions and principles are the basis for the synthesis of technical solutions. (Just one aspect of the field of bionic).	Nature	E.g., physical effects, structural data, process data

Cluster analysis	Homogeneous groups (clusters) are formed based on similarities. The aim is to create groups in which the objects within the group are as similar as possible, and the different groups are as dissimilar as possible. The cluster analysis process is divided into six steps: Select cluster variables, determine similarities, select fusion algorithm, determine cluster number, and interpret cluster solution.	Internal/ accessible database	E.g., product data, process data
Similarity analysis (CBR)	(Or case-based reasoning) Identify helpful information by searching for similar data. Support with CBR, by using similarity measures project data is found.	Internal/ accessible database	E.g., product data, process data
Trend analysis	First, an identification of the current developments occurs, and then a forecast of the future development is made. Trend analysis can be supported with various methods, such as trend scanning and monitoring.	Competition/ market/ research/ society	Potential future trends

Appendix D

Reference System Elements Used in Case Studies a, b, and c Sorted Into Three Categories According to Their Use in G_i's Development

Table D.1: Reference system elements used in the case studies a, b, and c sorted into three categories according to their use in G_i's development. Adapted from Albers, Kempf, et al. (2024).

Elements used as the basis for the development of the system of objectives of G_i	**Elements used as the basis for the development of the operation system of G_i**	**Elements used as the basis for the development of the system of objects of G_i**
$RSE_{i=n}^{a,1}$: Customer requirements documented in the engineering mandate	$RSE_{i=n}^{a,9}$: Creativity methods	$RSE_{i=n}^{a,2}$: Physical product of the previous system generation
$RSE_{i=n}^{a,4}$: Design drawings of the previous system generation	$RSE_{i=n}^{a,13}$: Internal development process	$RSE_{i=n}^{a,2}$: Physical product of the previous system generation
$RSE_{i=n}^{a,5}$: Calculation documentation of the previous system generation	$RSE_{i=n}^{a,14}$: Internal dimensioning (calculation and simulation) guidelines	$RSE_{i=n}^{a,7}$: Expert knowledge and experience of the engineering team
$RSE_{i=n}^{a,6}$: Simulation documentation of the previous system generation	$RSE_{i=n}^{a,18}$: Engineering methods described in standards and guidelines	$RSE_{i=n}^{a,10}$: Concepts developed based on creativity methods
$RSE_{i=n}^{a,8}$: Requirements derived from the previous system generation's wiki documentation	$RSE_{i=n+1}^{b,4}$: Standard formulation process for requirement formulation derived from the previous system generation's requirements	$RSE_{i=n}^{a,11}$: Prototypes of the system generation in development
$RSE_{i=n}^{a,17}$: Requirements for light sources described in standards and guidelines	$RSE_{i=n+1}^{b,8}$: Requirements management tool	$RSE_{i=n}^{a,12}$: Documentation of the validation of the prototypes
$RSE_{i=n+1}^{b,3}$: Standard format for requirement formulation derived from the previous system generation's	$RSE_{i=n+1}^{b,10}$: Method descriptions (e.g., guidelines or training documents) of requirements	$RSE_{i=n}^{a,15}$: Calculation and simulation model of the system generation in development

requirements	management activities	
$RSE_{i=n}^{c,6}$: Validation objective of the previous system generation	$RSE_{i=n+1}^{b,11}$: Expert knowledge and experience in the specification process	$RSE_{i=n}^{a,16}$: Documentation of the calculation and simulation results of the system generation in development
$RSE_{i=n}^{c,7}$: Specified test cases of the previous system generation	$RSE_{i=n}^{c,5}$: Expert knowledge and experience in the usage of the previous generation's (sub-)systems	$RSE_{i=n}^{a,19}$: Physical interfaces described in standards and guidelines
$RSE_{i=n}^{c,10}$: Variables of investigation from the problem analysis of a given problem	$RE_{i=n}^{c,16}$: Expert knowledge and experience in measurements of virtual torsion compensation	$RSE_{i=n+1}^{b,1}$: Requirements of the previous system generation
$RSE_{i=n}^{c,12}$: Requirements based on expert knowledge and experience of influences from the test environment setup on the test variables	$RSE_{i=n}^{c,17}$: Expert knowledge and experience in the use of axial force measurement in the force flow	$RSE_{i=n+1}^{b,2}$: Requirements from topic-specific requirement bundles
$RSE_{i=n}^{c,14}$: Requirements derived by problem analysis from measurements in the previous generation test environment		$RSE_{i=n+1}^{b,5}$: Reconstructed requirements of competitor vehicles
		$RSE_{i=n+1}^{b,6}$: Additional information on requirements (e.g., the person responsible for implementation or source)
		$RSE_{i=n+1}^{b,7}$: In-detail information on validation procedures (e.g., a certain driving cycle)
		$RSE_{i=n+1}^{b,8}$: Chapter structure of the previous system generation's requirements specification
		$RSE_{i=n}^{c,1}$: Characteristic attributes of the used previous system generation's (sub-)systems (from data sheets)
		$RSE_{i=n}^{c,2}$: Description of the previous generation's (sub-)systems interfaces
		$RSE_{i=n}^{c,3}$: Existing (digital) models (e.g., MATLAB simulation models) of the previous generation's (sub-)systems
		$RSE_{i=n}^{c,4}$: Documentation of existing (digital) models (e.g., MATLAB simulation models) of the previous system generation's (sub-)systems
		$RSE_{i=n}^{c,8}$: Principle sketch of the previous system generation
		$RSE_{i=n}^{c,9}$: Characteristics/parameters

Reference System Elements Used in Case Studies a, b, and c Sorted Into Three Categories According to Their Use in Gi's Development

		from the modeling of the tribological system and its interaction with the residual system and its environment from tests in the previous system generation
		$RSE_{i=n}^{c,11}$: previous system generation
		$RSE_{i=n}^{c,13}$: Design setup based on expert knowledge and experience on influences of the test environment setup on the test variables
		$RSE_{i=n}^{c,15}$: Design setup derived by problem analysis from measurements in the previous generation test environment
		$RSE_{i=n}^{c,18}$: Expert knowledge and experience on (dis-) advantages of different actuation principles

G_i: System generation i; RSE_i: Reference system element

Reference System Elements of Case Studies d, e, and f Allocated to the Reference System's Three Subsystems Using the Definitions of the Reference System of Objectives, the Reference Operation System, and the Reference System of Objects

Table D.2: Reference System elements of case studies d, e, and f allocated to the reference system's three subsystems using the definitions of the reference system of objectives, the reference operation system, and the reference system of objects. Adapted from Albers, Kempf, et al. (2024).

Reference system of objectives' elements	Reference operation system's elements	Reference system of objects' elements
$RSE_{i=n}^{d,1}$: Performance specifications of previous system generations	$RSE_{i=n}^{d,8}$: Own expertise and engineering mechanics' lecture notes	$RSE_{i=n}^{d,5}$: Current system generation (to specify the design of the interfaces)
$RSE_{i=n}^{d,2}$: Safety requirements descriptions	$RSE_{i=n}^{d,9}$: Creativity methods	$RSE_{i=n}^{d,7}$: Principles and mechanisms from 3D-printers
$RSE_{i=n}^{d,3}$: Experience of experts of the industrial partner	$RSE_{i=n}^{d,10}$: Product development methods	$RSE_{i=n}^{d,11}$: Templates for intermediate results
$RSE_{i=n}^{d,4}$: Validation results of their prototypes	$RSE_{i=n}^{d,13}$: Experience of the researchers	$RSE_{i=n}^{d,12}$: Templates for result presentation
$RSE_{i=n}^{d,6}$: Requirements of the interfaces reconstructed based on the current system generation	$RSE_{i=n}^{e,9}$: Dissertation describing the previous system generation	$RSE_{i=n}^{e,2b}$: Design catalogs (to identify functionalities to be implemented)
$RSE_{i=n}^{e,1}$: Requirements from the previous system generation	$RSE_{i=n}^{e,12}$: Software tools to set up and validate the optimization method already available	$RSE_{i=n}^{e,4}$: Functionalities to implement in the method derived from basic experiences described in the literature
$RSE_{i=n}^{e,2a}$: Design catalogs (to derive requirements)	$RSE_{i=n}^{f,5}$: Expertise in the machine domain	$RSE_{i=n}^{e,7}$: Documentation of the previous system generation
$RSE_{i=n}^{e,3}$: Requirements derived from basic experiences described in the literature	$RSE_{i=n}^{f,8}$: Documentation in software tools for agile collaboration	$RSE_{i=n}^{e,8}$: Dissertation describing the previous system generation
$RSE_{i=n}^{e,5}$: Experience and knowledge from manufacturing engineers and research projects		$RSE_{i=n}^{e,10}$: Code of the previous system generation's components
$RSE_{i=n}^{e,6}$: Coupling requirements from software developers		$RSE_{i=n}^{f,3}$: Kinematics and structure of previous machine generation
$RSE_{i=n}^{e,11}$: Test and experiment results of other research projects		$RSE_{i=n}^{f,4}$: Machine data analysis of actual machine usage
$RSE_{i=n}^{f,1}$: Existing gripping unit automation of laser-cutting machine		$RSE_{i=n}^{f,6}$: Interfaces of different automation solutions and machine tools

Reference System Elements of Case Studies d, e, and f Allocated to the Reference System's Three Subsystems Using the Definitions of the Reference System of Objectives, the Reference Operation System, and the Reference System of Objects

$RSE_{i=n}^{f,2}$: Existing gripper unit automation of punching machine		$RSE_{i=n}^{f,11}$: Modular system architecture of the previous automation solution generation
$RSE_{i=n}^{f,7}$: Typical part geometries for automated sheet metal part unloading		
$RSE_{i=n}^{f,9}$: Safety regulations and norms		
$RSE_{i=n}^{f,10}$: Knowledge of regularly occurring machine errors from sales or product management department		

RSE_i: Reference system element

Appendix E

Overview of Research Result Types Described in the Literature

Table E.1: Overview of the different types of research results categorized in the five clusters: publications, prototypes, equipment, data, and experience. Adapted from Kempf et al. (2024).

Type of research result	Source	Cluster
Equipment (used by firms)	(Bakouros & Samara, 2010)	Prototype
Instrumentation (used by firms)	(Bakouros & Samara, 2010)	Prototype
Skills	(Bakouros & Samara, 2010)	Experience
Human capital	(Bakouros & Samara, 2010)	Experience
Networks (of scientific and technological capabilities)	(Bakouros & Samara, 2010)	Equipment
Prototypes (for new products/ processes)	(Bakouros & Samara, 2010; European Commission)	Prototype
Instruments (scientific)	(David et al., 1992)	Equipment
Training (of scientists and engineers)	(David et al., 1992)	Equipment
Networks ((Social) for information diffusion)	(David et al., 1992)	Experience
Audio visual recordings	(European Commission)	Publication, prototype, data
(Computer) software	(European Commission; Mutz et al., 2012)	Prototype, equipment
Databases/ datasets	(European Commission; Marcondes, 2012)	Data
Technical drawings, designs, or working models	(European Commission)	Publication, prototype
Patents	(European Commission; Mutz et al., 2012)	Publication
Policy documents or briefs	(European Commission)	Publication
Reports (research or technical)	(European Commission; Hove, 2020)	Publication
Journal articles (peer-reviewed and non-peer-reviewed)	(European Commission; Hove, 2020; Mutz et al., 2012)	Publication
Conference proceedings	(European Commission; Mutz et al., 2012)	Publication
Book chapters	(European Commission)	Publication
Monographs/ books	(European Commission; Mutz et al., 2012)	Publication
Artefacts	(European Commission)	Prototype, equipment
Presentation slides	(Hove, 2020; Mutz et al., 2012)	Publication
Full-text papers	(Marcondes, 2012)	Publication
Algorithms	(Marcondes, 2012)	Prototype, equipment

Terminological knowledge bases	(Marcondes, 2012)	Publication, equipment
Virtual machines (that can process these data)	(Marcondes, 2012)	Equipment
Internet publication	(Mutz et al., 2012)	Publication
Staff development	(Mutz et al., 2012)	Experience
Antology	(Mutz et al., 2012)	Publication
Mass communication (e.g., newspaper article)	(Mutz et al., 2012)	Publication
Poster	(Mutz et al., 2012)	Publication
Thesis/ dissertation	(Mutz et al., 2012)	Publication
Degree	(Mutz et al., 2012)	Experience

Collection of Research Results From Four Research Projects to Evaluate the Research Results Classification Model Initially

Table E.2: Collection of research results from four research projects to evaluate the research results classification model initially. Allocation of the research results to the research readiness levels. Based on Kempf et al. (2024).

Project number	Research result	Cluster	RRL	Reasoning
#1	Optimization procedure (digital coupling model) of optimization and design tools implemented on a workstation	Prototype	2-6	Researcher evolved the procedure gradually, producing intermediate results on different maturity levels
#1	Illustration of the optimization procedure on slides	Publication	2-6	See above
#1	Conference publications of the optimization procedure	Publication	2-6	See above
#1	Scripts to couple different simulation and design tools, programmed in Python code	Prototype	7	Integrated into and validated within the optimization procedure
#1	Conference publication of the coupling scripts	Publication	7	See above
#1	New optimized designs (CAD parts) as results of the optimization procedure for validation	Data	1	Parts by themself are only data that serve for validation of other results
#2	Conference publication on the influences of fiber bundles and their appearance during the molding process on material quality	Publication	3	Concept of the influences validated via prototyping
#2	Visualization of the influence of fiber bundles on a material prototype	Prototype	3	See above
#2	Conference publication of recommendations for quality management and assessment for machinery manufacturers	Publication	7	Validated on the commercial machinery used by the researcher
#2	Prototype of monitoring technology to monitor the quality of the produced parts	Prototype	6	No integration into the machinery during the project
#2	Conference publication of the monitoring technology	Publication	6	See above
#2	STL-files (images) of plastificat	Data	1	
#2	Journal publication of the plastificat images	Publication	1	
#2	Seminars (presentation, handout) on the processing for practitioners	Publication	9	Seminars currently offered to practitioners

#3	Journal and conference publications of data representing material properties (tensile, impact, bending, creep testing)	Publication	1	
#3	Modeling approaches/ hypotheses for material behavior description (algorithms on a server)	Prototype	4	Validated in a laboratory environment
#3	Journal publication of the modeling approaches/ hypotheses	Publication	4	See above
#3	Images of microscopy on fiber orientation	Data	1	
#3	Journal publication of the images	Publication	1	
#3	Coded scripts for data analysis	Equipment	9	Used in the research project
#4	Mathematic model (differential equations) including the material parameters for viscoelastic modeling of, e.g., polyamide (PA) implemented on a workstation	Prototype	4	Validated in a laboratory environment using experimental data
#4	Journal publication of the mathematic model	Publication	4	See above
#4	Exemplary material parameters (diagrams) for load case behavior considering different moistures	Prototype	2	Diagrams represent the estimated behavior of the material system
#4	Journal publication of the exemplary material parameters	Publication	2	See above
#1, 2, 3, 4	Bachelor and master graduates	Experience	9	Graduates start working in practice
#1, 2, 3, 4	Bachelor and master degrees	Experience	8	Certificates of the graduates attesting the skills and knowledge
#1, 2, 3, 4	Skills in scientific work	Experience	8, 9	
#1, 2, 3, 4	Networks with fellow researchers and corporate partners	Experience	9	

Appendix F

Interview Guideline to Explore the Reasons and Triggers, Challenges and Barriers, and Methods and Tools of Searching for and Applying Reference System Elements from Research Results in Corporate Product Engineering

Using references from university research in company product development – Interview script

The traditional goal of university research is the gain of knowledge, while companies aim to create innovations to be successful on the market. Hereby, university research is usually gaining cutting-edge knowledge or developing leading edge technologies and methods. Therefore, university research (in addition to other projects in the company or competitors) can be a valuable source of knowledge that can serve as a basis and starting point for the development of the new products. Improving the usability of knowledge from university research in corporate product development projects is the main objective of our research.

To be able to support this knowledge transfer (also in the sense of new technologies or technical systems) from university research into company product development projects, the major objectives of this study are to investigate the:

- current use of knowledge from university research in companies
- reasons/ benefits of using knowledge from university research in companies
- barriers and success factors for the use of knowledge from university research in product development projects of companies

General questions

1. What is your position within the company? How are you involved in the product development process?
2. What is your work experience and background?

All sources of knowledge

When developing a new product, companies do not start from scratch. Usually, they take reference on already existing elements/existing knowledge, so the development time and risk of the project can be reduced. These references are the starting point to develop the new product. The core activities are to decide what to carry over and what to develop newly. Striking examples are:

- Tesla: using cells from laptops for their first car
- Germans: Patent of Nylon (US) to develop Perlon in Germany
- Haber-Bosch-Process (ammonia synthesis): Carl Bosch industrialized the process Fritz Haber developed at KIT in Karlsruhe

3. Do you agree with this understanding of product development? Are there any open questions to this understanding?
4. What are the main sources for references used within your company?
5. How do you search for these references? Are there any tools or methods you use for this search?
6. What are the major challenges to face?

Knowledge from university research

Example: Within a university research project of shape/topology optimization, a doctoral researcher is developing a methodology to link several tools and programs to automate the workflow for the optimization of sheet parts made of a new material system. To do so, he includes and links tools of CAD, mapping and structural analysis. Scripts are necessary to translate the output of one to the input of the following tool. As results of this research project, there will be in the end:

- Optimized workflow (diagram) linking the different tools
- (Python) code to link the tools and run the optimization
- Results of the simulation and optimization (new initial design of optimized part)
- Experience on how to model such workflows
- Papers and thesis presenting the results

7. Does your company make use of references from university research when developing new products? Can you give examples? (If not, why?)
8. In which situation are you using references from university research – what are triggers/ reasons for using references from university research?

9. In what kind of projects do you use references from university research? In which stages of the projects?
10. What has to be done with the references from university research to apply them in the company?
11. What do you use references from university research for?
12. What are the benefits of using references from university research?
13. How do you look for references from university research? Do you use/ follow specific methods or tools?
14. What are challenges or barriers of using references from university research when it comes to:
    a. identification?
    b. application in corporate product development projects?
15. What are success factors for using references from university research in your company?
16. Would you cherish additional information supplementing the references from university research? What information? (What would the “perfect” reference from university research look like?)

Closing

17. What are the top sources for references to develop a successful new product (innovation)?
18. Is there anything else you want to add before we close the interview?

Reasons for Using Research Results as Reference System Elements in Corporate Product Engineering Identified in the Interview Study

Table F.1: Reasons for using research results as reference system elements in corporate product engineering identified in the interview study. Adated from Kempf, Schlegel, et al. (2023)

Category	Reason	Interview
Reliable sparring partners	Sparring partner for pushing (e.g., physical) limits	I9
	Reliable and persistent partners that will not perish suddenly	I9
Open communication	Neutral communication: honest, trustful, no politics	I1, I7
	Open communication: no hiding information	I1
	Possibility to talk to the researchers to collect implicit knowledge	I6
High qualification	Highly qualified experts	I2, I9
High-quality reference system elements	Solid knowledge base to set up as a starting point when diving into new applications/ processes	I2, I3, I6
	Providing basic data/ knowledge	I7, I8
	Open knowledge, free to use (regarding IPR)	I4
	New/neutral perspective, overcoming company blindness	I1, I2, I3, I4, I7
	Receiving general results with many potential product applications	I1, I6
	Gaining in detail knowledge, fundamentals, and principles of new technologies	I1, I3, I9
Competitive advantage and mastering complexity	Staying up-to-date	I2, I6, I9
	Competitive advantage because of on-the-edge technologies/ knowledge	I2
	Great (only) inspiration and development partner if the company is leading in its field	I4, I9
	Highly complex problems can only be solved by the collaboration of many highly qualified people	I9
	Necessary to participate in the high development speed due to the huge research communities	I2, I4, I9
Cost and time efficiency	Existent knowledge base: cost and time saving compared to doing all in-house	I2
	Cheap (a lot of funding)	I1
	A lot of knowledge is accessible in a short period of time	I2
	Commissioned development work: cost and time saving compared to doing all in-house	I7
Marketing and image	Can be used as demonstrators/ argument when approaching (potential) customers	I8
	Marketing/ image	I9

Short Descriptions of the Identified Challenges and Barriers

Table F.2: Short descriptions of the challenges and barriers from practice exacerbating the search for and/ or application of reference system elements from research. Based on Kempf, Thapak, et al. (2023).

Challenge/ barrier	Short description
Research result-related challenges and barriers	
Unclear use case/ application	The possible use case or application of research results as RSEs in corporate engineering is hard to perceive.
Unclear benefits bundle	The benefits of research results as RSEs for corporate engineering in terms of provider, customer, and user benefits are unclear.
Unclear reliability/ maturity	RSEs from research require in-house validation.
Unfitting RSE environment	The research result's tools, parts, or environment do not fit the company's available tools, parts, or environments (e.g., simulation environment but also in terms of human factors such as emotions).
Neglected interdependencies of product and production	Research results are developed neglecting dependencies of, e.g., technologies, materials, or (sub-) systems and the production process.
Neglected systemic interrelations	Research results are sub-system specific and neglect interrelations and connections to other sub-systems.
High disciplinarity	Research results are discipline/ sub-system specific and neglect interrelations to other disciplines and sub-systems.
Missing information	Research results lack information on details (e.g., additives in materials) or boundary conditions (e.g., used simulation tool environment).
Excessive positivity	Published research results show what works well and neglect to present limitations and failures.
High generality	Research results are on a general level where specifics are simplified (e.g., process models neglecting individual skill sets or motivation of engineers).
Lacking professionalism	The tools, parts, or environment used for the research result do not fulfill professional standards.
Insufficient consideration of corporate needs	There is a mismatch to corporate needs when research results are generated without considering and analyzing these needs correctly.
Unpopular research jargon	Researchers use their research field-specific jargon to describe/ represent research results. This increases the effort for corporate engineers to understand the research results.
High specificity	Research results have a high specificity (e.g., regarding material processing). In this case, they just work for exactly one set of conditions (e.g., components and additives in a material system).
Unattractive representation format	Research results are represented in unattractive formats such as research papers. These require high mental effort to process, are monotonous, and do not fit the current way of processing information (e.g., few pictures and a lot of text in papers).
Research-related challenges and barriers	
High amount of research results	The high amount of different (/ alternative) research results exacerbates identifying a suitable RSE from research.
Unsatisfying intellectual property regulations	Research results are freely available to everyone. This can complicate patentability and the advance to competitors.

	Furthermore, this can complicate the initiation of collaborative developments. On the other hand, research facilities can insist on keeping all intellectual property. This can complicate the application.
Neglected profitability	Profitability is no requirement of the research results.
Long development time in research	The duration of research projects to gain results exceeds the (available) time a company is willing to wait for results. The usual development time in research is three to five years compared to three to five months up to one or two years in companies.
Company and corporate engineer-related challenges and barriers	
High progressiveness	Research results are too advanced for the current status of the company.
Lacking technological/ scientific expertise of management	The company’s management lacks the technological/ scientific expertise to realize the value of RSEs from research (e.g., especially if they are not engineers themselves).
High rigidity of engineers and company	The mindset, experience, and knowledge of in-house technologies and existing engineering environments (e.g., tools) are barriers to approaching or using RSEs from research (e.g., new knowledge, technologies, processes, or methods).
Missing expertise	Corporate engineers lack the expertise to understand (complex) research results (e.g., if they want to broaden their portfolio).
Limited grasp	It takes too long to grasp the potential benefits bundle of (complex) research results as RSEs.
Search/ application process-related challenges and barriers	
Difficult scalability	The scaling from a lab scale to a corporate scale is a barrier to implementing RSEs from research.
High time investment for implementation	The search and application of RSEs from research takes more time than relying on experience and knowledge of in-house technologies.

Appendix G

Measures to Improve Research Results' Usability as Reference System Elements in Corporate Product Engineering

Table G.1: 66 measures addressing the three target groups. Adapted from Kempf et al. (2025).

Measures for corporate product engineers and companies	Measures for researchers and Research facilities	Measures for funding agencies and (research) policymakers
Translating research question	Stakeholder-specific preparation of results	Requesting specific use cases
Mindset for failures	Presentation of partial results via success stories	Transparent communication of the shift in goal/focus
Dismissing the need for ROI in research projects	Publication of learnings from "failures"	Offering (flexible) funding for demonstrators
Central repository for research results[F/P, R]	Ensuring quality and use case relation by, e.g., using reporting templates for research results or standardizing the preparation of methods (e.g., methods development kits)	Enabling easy and direct exchange between policymakers, companies, and research
Preparation and presentation of the concepts in the corporate context to present to the management	Developing competencies (integrated with company and research) such as "transfer to teaching" using, e.g., competency navi	Requesting specific work packages for transfer within projects (+ funding of, e.g., transfer platforms)
Explaining abstract concepts by explaining benefits (e.g., economic, technological, methodical, organizational, administrative) in terms of, e.g., business case, interpretation/ transferability[R]	Early involvement of companies (reflection canvas) by, e.g., co-creation workshops with interdisciplinary teams, using reflexive methods (e.g., sprints/ agile approaches and methods/ adaption/ process step/ project) to reach honest reflection in the consortium + company + politics/ funding agencies	Offering long-term funding for the operation of results and transfer platforms
Integrating intermediaries, e.g., transfer and competence centers or consultancies/ service providers	Improving transferability by, e.g., integrating best practices, involving company partners, collecting requirements, publishing results and methodology	Ensuring the continuation by, e.g., working groups, initiatives, standards, associated partners
Providing enough time for research/ investigations	Considering a specific use case (building an industry research tandem)	Simplifying/ accelerating the application process

Staying close to research facilities (in terms of staff)	Videos with corporate partners, etc. (Interviews, Q&A)	Requesting/ offering contact persons beyond the end of the project
Capability to analyze research repositories methodically[F/P, R]	Focusing on public relations and evolving research communication (e.g., involving PR agencies)	Requesting/ offering transfer roles in the consortia
Decreasing obstacles for cooperative formats	Focusing on Open-Source Science, Open Access (including data and algorithms)	Increasing transparency in the evaluation of success
Providing R&D budget	Considering the transfer to other companies	Supporting start-up
Budget for high-risk projects	Requesting and promoting publications from working groups, committees, etc.[F/P]	Requesting/ including additional funding from companies
Specific user-oriented addressing of benefits, boundary conditions, limitations, and comparable examples[R]	Synchronizing "jargon"/ wording (two languages: paper vs. natural language) by, e.g., using publications as a basis for discussions (not only presentation of results, talking with each other, using graphical representation (if possible, using standardized systems such as UML), guided tours/ open house, events for exchanges	Adding KPIs after project run time to the evaluation (e.g., successful transfer of technologies)
Transferring research results to company-related examples	Using personal networks to transfer to companies that are not involved	Improving the conditions for open-access publication
Offers with differentiated entry points, requirements for the company, and support services[F/P, R]	Improving research communication by using a common language within the project (including, e.g., expanded internal knowledge management, glossary)	Flexible follow-up funding of projects, including, e.g., time buffer for follow-up projects (for bridging)
	Focusing on use cases at conferences	Considering user needs for call formulation
	Visualizing the big picture at conferences	Requesting best practice formalization
	Additional paper chapter: risks and benefits using a specific case study	Requesting/ offering a central exchange platform with sponsors (online)
	Basic funding (stipends, funding projects, industrial projects) [F/P]	Including politicians as a multiplier and supporter to increase the visibility of results
	"Reducing" the long development time by, e.g., reducing formalization, breaking down the task into sub-work packages, sharing of intermediate results (e.g., through retrospectives), adjusting proposals to possible agile working formats[F/P]	Enabling flexible proposals to extend the consortium, funding, and funding period
	Increasing Venture Capital for research[C]	Connecting developers/ users

	Ending "publish or perish" (often publications are the only success factor)	Providing contact persons who help with/ expedite applications
	Considering interfaces within project calls[F/P]	Looking for (external) investors
		Considering trends for call formulation
		Stressing known barriers

[R] Relevant for researchers/ research facilities, too.

[F/P] Relevant for Funding agencies/ (research) policymakers, too.