Thesis for The Degree of Doctor of Philosophy

Industrial adoption of new design methods

Guiding sustainable design and collaboration in the manufacturing industry

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Gothenburg, Sweden, 2026

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Cover image: Abstract illustration of a design method lab in close contact with the manufacturing industry. Both of which are influenced by, and vice versa influence, society.

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Abstract

The manufacturing industry needs a rapid shift in how products are designed and produced to better contribute to sustainable production and consumption. This, together with emerging technologies, upcoming legislation, and changing market trends, drives a sustainability transition in manufacturing companies, and *design* has been identified as a crucial enabler of this transition. Therefore, *design researchers* have proposed several design methods to support adequate integration of sustainability in their design processes.

Despite their evidenced benefits, the industrial adoption of such design methods remains underutilized, an issue that has persisted and been continuously raised for more than 20 years in the 'design domain'. This is a multifaceted issue, and previous research has identified several barriers and enablers to adoption, ranging from recommendations to modify, simplify, or 'improve' these design methods, to promoting the use of qualitative data. Although many of these enablers have proven successful, the industrial adoption of design methods remains a contemporary issue. At the same time, *change* has been thoroughly treated in the 'management domain', and there is an underutilized body of knowledge that can be used to better understand why this issue persists and to strengthen practical contributions, thus contributing to the design community. This research, therefore, adopts an interdisciplinary perspective to study industrial adoption, employing several methods to collect and analyze qualitative empirical data together with actors in the Swedish manufacturing industry, including action research, case studies, participant observation, Glaserian grounded theory, questionnaires, and interviews.

There are four main contributions of this research: (i) A descriptive framework that captures 53 interdisciplinary barriers and enablers to the industrial adoption of design methods. The framework incorporates process and methodological, organizational, and human-behavioral perspectives, capturing several factors typically scattered across research domains; (ii) Two new concepts are proposed, the *dualism of design methods* and the *situational design problem*. These, in turn, clarify the role of design methods in a sustainability transition and also clarify the key barriers to industrial adoption; (iii) A needs-driven and collaboration-based adoption approach that guides industrial adoption by supporting researchers and practitioners to adapt design methods; (iv) An interactive method to guide the assessment of a collaborative ecosystem's ability to share and manage sustainability information and data.

Keywords Design methods, Sustainable design, Design, Change management, Collaboration, Information and data management, Manufacturing industry

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper A**] **Mallalieu, A.**, I. Hallstedt, S., Isaksson, O., Watz, M., & Almefelt, L. (2024), *"Barriers and enablers for the adoption of sustainable design practices using new design methods – Accelerating the sustainability transformation in the manufacturing industry". Sustainable Production and Consumption, Volume 51, pp. 137-158.*
DOI: 10.1016/j.spc.2024.08.023.

Author contribution: Mallalieu served as the first author and led the planning and writing of the paper. Mallalieu also led the data collection and analysis, with support from the remaining authors. The co-authors provided continuous support throughout the writing process.

[**Paper B**] **Mallalieu, A.**, Martinsson Bonde, J., Watz, M., Nylander Wallin, J., I. Hallstedt, S., & Isaksson, O. (2023), *"Derive and Integrate Sustainability Criteria in Design Space Exploration of Additive Manufactured Components". In Proceedings of the Design Society. Volume 3: ICED23, July 2023, pp. 1197-1206*
DOI: 10.1017/pds.2023.120.

Author contribution: Mallalieu served as the first author and led the planning and writing of the paper. Mallalieu also coordinated, planned, and facilitated the activities required to conduct the case study with Dr. Martinsson Bonde and Dr. Sandgren Watz. The remaining co-authors supported the research activities and the writing process.

[**Paper C**] **Mallalieu, A.**, Sandgren Watz, M., Isaksson, O., I. Hallstedt, S., & Almefelt, L., *"From design methods to practice: guiding adoption of sustainable design in manufacturing companies"*
Under Review in Journal.

Author contribution: Mallalieu served as the first author and led the planning and writing of the paper. Mallalieu also coordinated, planned, and facilitated the activities required to conduct the case study with Dr. Sandgren Watz. Mallalieu led the data collection and analysis, with support from the co-authors. The co-authors also provided continuous support throughout the writing process.

[**Paper D**] **Mallalieu, A.**, Isaksson, O., I. Hallstedt, S., Sandgren Watz, M., Dokter, G., & Almefelt, L., *"Sharing and managing sustainability information and data in collaborative ecosystems – Insights from testing a novel assessment method with the automotive industry"*
Resubmitted to Journal after first review.

Author contribution: Mallalieu served as the first author and led the planning and writing of the paper. Mallalieu also coordinated, planned, and facilitated the main activities required to conduct the case study. Mallalieu led the data collection and analysis, with support from the co-authors. The co-authors also provided continuous support throughout the writing process.

[**Paper E**] Brahma, A., Hajali, T., **Mallalieu, A.**, Isaksson, O. (2025), *"A risk analysis method for implementation of additive manufacturing". Journal of Engineering Design, Volume 37, pp. 311-338.*
DOI: 10.1080/09544828.2025.2489641.

Author contribution: Mallalieu served as the third author and supported the writing process by providing feedback. Moreover, Mallalieu, together with Hajali, coordinated, planned, and facilitated the preceding activities required to conduct the study, including observations and engagements with industrial actors, aimed at mapping and analyzing workflows and clarifying the study's motivation. Dr. Brahma, together with Hajali, led the development and testing of the method. Professor Isaksson supported these preceding activities and the writing process.

Other publications

The following list includes additional contributions published during my PhD studies.

[**a**] Carlsson S., **Mallalieu, A.**, Almefelt L., & Malmqvist, J. (2021), *"Design for Longevity - A Framework to Support the Designing of a Product's Optimal Lifetime". In Proceedings of the Design Society, Volume 1: ICED2021, August 2021, pp. 1003-1012 DOI: 10.1017/pds.2021.100.*

[**b**] **Mallalieu, A.**, Hajali, T., Isaksson, O., & Panarotto, M. (2022), *"The Role of the Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing". In Proceedings of the Design Society, Volume 2: DESIGN2022, May 2022, pp. 1401-1410 DOI: 10.1017/pds.2022.142.*

[**c**] Martinsson Bonde, J., **Mallalieu, A.**, Panarotto, M., Isaksson, O., Almefelt, L., & Malmqvist, J. (2022), *"Morpheus: The Development and Evaluation of a Software Tool for Morphological Matrices". In Proceedings of NordDesign 2022 DOI: 10.35199/NORDDESIGN2022.38.*

[**d**] I. Hallstedt, S., Isaksson, O., Watz, M., **Mallalieu, A.**, & Schulte, J. (2022), *"Forming Digital Sustainable Product Development Support". In Proceedings of NordDesign 2022 DOI: 10.35199/NORDDESIGN2022.37.*

[**e**] Hajali, T., **Mallalieu, A.**, Brahma, A., Panarotto, M., Isaksson, O., Stålberg, L., & Malmqvist, J. (2023), *"Information Flow Analysis Enabling the Introduction of Additive Manufacturing for Production Tools- Insights from an Industrial Case". In Proceedings of the Design Society, Volume 3: ICED23, July 2023, pp. 2315-2324 DOI: 10.1017/pds.2023.232.*

[**f**] Isaksson, O., Brahma, A., Hajali, T., Ohlsson, D., & **Mallalieu, A.** (2024), *"The Importance of Digitalisation in Industrialising Additive Manufacturing: Learnings from the DIDAM P2030 Project", In Sustainable Production through Advanced Manufacturing, Intelligent Automation and Work Integrated Learning, April 2024, pp. 442-452, IOS Press DOI: 10.3233/ATDE240187.*

[**g**] **Mallalieu, A.**, Jonasson, A., Petersson, A., Rosendal, M., I. Hallstedt, S., Almefelt, L., & Isaksson, O. (2024), *"Sustainability Criteria for Introducing New Technologies in Low-Income Contexts". In Proceedings of the Design Society. Volume 4, DESIGN2024, May 2024, pp. 1359-1368 DOI:10.1017/pds.2024.138.*

[**h**] **Mallalieu, A.**, & Riehl, K. (2024), *"Sport4STEM". Technical Report, SDG Olympiad, Paris, September 2024 DOI: N/A.*

[**i**] Dokter, G., **Mallalieu, A.**, I. Hallstedt, S., & Isaksson, O. (2025), *"Collaboration Towards the Design of Sustainable and Circular Value Chains: Reviewing the State-of-the-Art in Literature and Practice". In Proceedings of the 6th Product Lifetimes and the Environment Conference, June 2025*
DOI: 10.54337/plate2025-10294.

[**j**] Isaksson, O., I. Hallstedt, S. I., Sandgren Watz, M. **Mallalieu, A.** & Björklund, H. (2025)., *"Roadmap to Enable Sustainable and Circular Designs in Collaborative Automotive Ecosystems". In Proceedings of the Design Society, Volume 5: ICED25, August 2025, pp. 2811–2820.*
DOI: 10.1017/pds.2025.10295.

[**k**] Léonard, P., I. Hallstedt, S., Isaksson, O., Kipouros, T., & **Mallalieu, A.** (2025), *"Key elements to navigate sustainable product development in aerospace". In Proceedings of the Design Society, Volume 5: ICED25, August 2025, pp. 2191-2200*
DOI: 10.1017/pds.2025.10233.

[**l**] Persson Schön, P., Eckert, C., **Mallalieu, A.**, & Bergsjö, D. (2026), *"Project Complexity and Cost Escalation in the Early Design of Railway Megaprojects". In Proceedings of the Design Society. Volume 6, DESIGN2026*
DOI: N/A.

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I also want to thank all my wonderful students over the years! Teaching has, for sure, been an unexpected bonus over these five years. It is very rewarding to see students learn new things and overcome their struggles. You have also brought a lot of energy into my everyday work life with your creativity and ideas. It has been a great opportunity for me to share my own experiences from the Mechanical Engineering program, bring in insights from my research, and practice my leadership skills. Hopefully, I have not bored you too much, and I have met my two personal teaching goals: inspiring at least one or two to pursue a PhD, and convincing all of you that product development is life.

I am also extremely grateful for my family, Mom & Dad; the result of you two shines through this work. Theo, Nova, Disa, and Felicia, everybody should have a large sibling team like you, and this would not have been possible without you. Finally, I consider myself lucky to have many close friends and family who deserve to be mentioned by name, but for different reasons, I chose to (only) mention my cousin Felix by name. But do know that the comfort and joy you give me, along with experiences we share, are what make this topic important to me. It gives me the inner motivation to help others get a fair chance at a life as good as the one I have. As a 'wise man' said (i.e., me now): *don't forget to live the life you are trying to create.*

Adam Mallalieu, Gothenburg, May 2026

Contents

Chapter 1

Introduction

First, this chapter presents the role of the manufacturing industry in the sustainability transition, which underpins the need for this research. Second, the role of design and design methods in supporting manufacturing companies during such a transition is clarified, which is the focus of this research. Third, within this topic, the specific research problem addressed in this thesis is outlined. Following this, the research aim and questions are presented. Lastly, the research setting, the scope and delimitations, and the overall structure of the thesis are presented.

1.1 The role of the manufacturing industry in a sustainability transition

The manufacturing industry plays a crucial role in society and is instrumental in transitioning to a sustainable society (World Economic Forum, 2023). On the one hand, the manufacturing industry has been, and remains, responsible for many of the products we design, produce, and use that have improved the everyday lives of many people over the last 100+ years, targeting different types of needs (Maslow, 1943). Ranging from targeting essential needs, such as the transport of medicines and food, or prosthetics that make life more fair, to needs that make life a more fun and exciting experience. For example, enabling more people to travel across the world to experience different cultures to a greater extent than before, such as visiting the impressive *Colosseum*, a historical landmark of the *Ancient Roman Empire*. Or, experience and relive 80s concerts, such as *Queen's* famous performance at *Live Aid*, and re-experience iconic movie scenes such as *Portals* in *Avengers Endgame* or the *Ride of the Rohirrim* in *The Return of the King*. All of which the author occasionally does using UHD TV screens and floor-standing speakers equipped with the latest 5.25-inch low-loss elements, somewhat making up for being born at the end of the 20th century. On the other hand, there is a downside to these new products and technologies: their production and use, for example, currently contribute significantly to increased greenhouse gas emissions, resource consumption, waste generation, and social issues across the value chain.

The sustainability transition, at large, needs to address several complex challenges, including poverty, climate change, resource scarcity, biodiversity loss, and inequality (United Nations, 2022), and is thus systemic and significant – and the manufacturing industry cannot, of course, be held solely accountable for such challenges. We are, nevertheless, reaching a critical stage at which irreversible effects will occur if society continues on the same trajectory (Rockström et al., 2023), whereas parts of global society are already facing severe consequences from this negative development. It is estimated that 3.3 to 3.6 billion people live in contexts highly vulnerable to climate change (United Nations, 2022). Many of these vulnerable communities are already suffering severe consequences from climate change (Mutanga et al., 2013) when, at the same time, the African continent, for example, has been responsible for less than four percent of the world's carbon emissions during the last 20 years (i.e., between 2000-2023, e.g., Statista, 2026). In turn, this calls for a sustainability transition on several levels, including the global economy, policies, business models, and the way we *design*, produce, and consume products – thus, although the manufacturing industry remains responsible for meeting the many different needs, it needs to do it in a sustainable way.

In line with this, upcoming legislation and policies also push the manufacturing industry towards this sustainability transition, part of Europe's eco-design and sustainable product regulations (European Union, 2024). Examples include *The EU taxonomy*, *The Digital Product Passport*, *The EU green deal*, and *The End-of-life vehicles regulation* specifically for the automotive industry. There are also voluntary agendas, such as the *Science-Based Targets* (SBTi, 2026) and the *The Sustainable Development Goals* (United Nations, 2026b), to which organizations explicitly commit. This, for example, imposes greater lifecycle responsibility on manufacturing companies and bans certain materials and chemicals. Thereby influencing which types of products can be produced and used, ultimately requiring the integration of radical, and occasionally disruptive, technologies into future solutions. Contemporary examples include new services enabled by emerging digital technologies, circular strategies and practices, and electrified powertrains, and much ongoing research and resources are targeted both nationally and internationally to support manufacturing companies in this change (e.g., European Commision, 2021; Vinnova, 2024a; ACARE, 2022). Despite efforts, the manufacturing industry struggles to implement the radical changes required to align with sustainable production and consumption at a sufficient pace (United Nations, 2026a; Bengtsson et al., 2018; Ceschin and Gaziulusoy, 2019).

1.2 The role of design and design methods in a sustainability transition

In parallel, the role of *design* has been widely recognized as a crucial enabler of the sustainability transition (e.g., Klotz et al., 2018; Baldassarre et al., 2020), and even at the European level (e.g., European Environment Agency, 2017). To elaborate on this in a broader sense, Gregory (1966) stated that *design*:

> "Is a pattern of behavior employed in inventing things of value that do not yet exist."

In line with this, Nobel Laureate Herbert Simon (1969) stated that

> "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" [...] and that designing "is concerned with how things ought to be, with devising artifacts to attain goals."

To some extent, *"design is everything"*, or at least as Willem (1990) stated:

> "All human-made things, material and immaterial, were designed at one time."

Over time, *designing* as a human act has been treated in different research domains and literature fora, generally argued beneficial to address *design problems*, i.e., problems that are not easily understood, which tend to be referred to as 'creative', 'ill-structured', 'ill-defined', 'wicked', 'open-ended', and 'unique' (Arnold, 1956; Simon, 1969; Rittel and Webber, 1973; Archer, 1979; Buchanan, 1992; Dorst, 2006; Dorst, 2011; Auernhammer and Roth, 2021; Gericke et al., 2022). Designing can generally be viewed as an iterative knowledge-producing process that supports designers or design teams to better acquaint themselves with the design problem and its potential solutions, where the overall goal is to identify a good problem-solution fit (Cross, 1992; Ullman, 1992; Dorst and Cross, 2001; Dorst, 2006). Or, in short, to propose a 'better' product (Cross, 2023b; Blessing and Chakrabarti, 2009). Examples of activities within this design process are:

- Interviewing and observing users to, e.g., obtain insights about their needs and expectations.
- Benchmarking similar products to, e.g., find flaws, identify and formulate new functions, and provide inspiration for integrating new sub-solutions.
- Studying upcoming technologies that can, e.g., bring new functionality or improve existing.
- Using brainstorming techniques to, e.g, explore novel concepts and solutions.
- Drawing concept illustrations to, e.g., refine and communicate them.

- Defining and setting geometry using computerized tools to, e.g., detail the solution.
- Searching in material databases, e.g., to identify suitable materials.
- Engaging and discussing with internal experts, but also suppliers, to e.g., acquire multidisciplinary input
- Prototyping and testing alternative concepts to, e.g., find out what works in practice.
- Modeling and simulation of alternative solutions to, e.g., predict behavior and support decision-making.

Design researchers have proposed a plethora of rigorously developed and tested design methods that support design activities in various ways (not exclusively for sustainability), with each method serving a different purpose (e.g., Blessing and Chakrabarti, 2009; Gericke et al., 2022). Design methods are effective at transferring design know-how to designers, i.e., knowledge of how to perform specific design activities, such as those listed above. They are occasionally referred to as ‘formalized’, ‘theory-based’, and/or ‘industry best’ practices (Eder, 2009), which reduce development time and costs, rationalize the design process, and improve communication (Ulrich & Eppinger, 2016).

For *sustainable design*, the early phases have been highlighted as crucial for producing relevant knowledge and integrating sustainability appropriately (e.g., Bhander et al., 2003; Ramani et al., 2010; Hallstedt et al., 2023b). It is typically stated, though not empirically proven, that 80% of a product’s impact is determined during these phases, as key decisions are made about requirements, materials, suppliers, and manufacturing methods. However, although critical, many designers and design teams struggle to adequately integrate sustainability into their design activities (Vilochani et al., 2024). Sustainable design introduces additional complexity to an already time-pressured designer, disrupting their current ways of working, pushing the designer to, for example:

- Interpret and translate long-term organizational targets into operational targets for their component or product.
- Assess and evaluate alternative concepts from a larger set of requirements, while also expanding the scope to include more lifecycle phases.
- Be aware and up-to-date on what materials are preferably used, are allowed but preferably not used, and are forbidden to use.
- Collaborate with a larger set of stakeholders internally and externally to ensure valid data and relevant perspectives are considered.
- Understand and assess what impact their component or product has on a system level, e.g., impact on the planetary boundaries.

- Make decisions on ambiguous data, and consider aspects not necessarily taught within their formal educational background, such as human rights or equality in the value chain.

Sustainable design is thus generally argued to require new skills and knowledge, as well as the adoption of several new design methods (Faludi et al., 2020; Hallstedt et al., 2023a). Therefore, to support designers and design teams in integrating sustainability, such as those listed above, several new design methods and tools for sustainable design[1] have been developed and disseminated by design researchers over the past 20 years (e.g., Luttropp and Lagerstedt, 2006; Faludi et al., 2020; Hallstedt et al., 2023a).

1.3 Industrial adoption and the research problem

Unfortunately, the industrial adoption[2] of new design methods proposed by design researchers is challenging and has been a raised issue for more than 20 years in the 'design domain' (Ritzén and Lindahl, 2001; Karlsson and Luttropp, 2006; Gericke et al., 2020; Vicente and Camocho, 2024). Furthermore, throughout this 20-year period, several challenges to the industrial adoption of design methods have been raised and appear to have remained somewhat consistent (Araujo et al., 1996; Ritzén and Lindahl, 2001; Lindahl, 2006; Wallace, 2011; Gericke et al., 2020; Vicente and Camocho, 2024). In summary, designers typically consider these proposed design methods as:

1. Not adding value or clear benefits
2. Too complex
3. Too time-consuming
4. Requiring too much effort
5. Too formalized
6. Incompatible with, and disrupting, the current ways of working
7. Requiring information and data that are lacking

Additionally, there is a general perception among designers that both support and commitment from management are lacking, thereby amplifying the influence of these challenges.

[1] For simplicity and to maintain consistency throughout this thesis, the term "design method" will be used when discussing design methods and tools for sustainable design. Also, Gericke et al., 2022 provide a more nuanced distinction between design method and tool.

[2] Adoption is here defined as "accepting or starting to use something new" (Cambridge, 2024). Adoption can, however, be partial, meaning that instances or facets of a design method are adopted.

Several research efforts have sought to address these issues in different ways, ranging from general guidelines such as using qualitative data, educating personnel, and making use of champions, to selecting and adapting design methods (e.g., Eder, 1998; Ritzén and Lindahl, 2001; Johansson, 2002; Lindemann, 2002; Ernzer and Birkhofer, 2002; O'Hare et al., 2010), and many of these are still raised as success factors (e.g., Faludi et al., 2020; Gericke et al., 2020; Brones et al., 2021; Lavrsen et al., 2022; Vicente and Camocho, 2024). One recurring strategy is to modify, simplify, or 'improve' the design methods from a process and methodological perspective to ensure they align with the existing design practices. Booker (2012), for example, claimed that it is important to ensure:

> "Integration with existing tools to maximize usability and acceptance."

Whereas, Eder (1998) stated:

> "Some methods fit better with one organization than with another. Each method must be adapted to that organization."

Vicente and Camocho (2024) instead propose an eligibility criterion stated:

> "Must be aligned with the needs of designers, available resources and project objectives."

Moreover, a relatively recent position paper (Gericke et al., 2020) elaborates on industrial adoption and similarly argues that design methods must fit the unique context in which they are used, thus serving as a key enabler. However, Gericke et al. (2020) do not specify how such adaptation should be made in practice, and the issue of how to appropriately adapt design methods has been raised in prior literature, as the design process takes many forms and adaptation depends on multiple factors (Ritzén and Lindahl, 2001; O'Hare et al., 2010; Gericke et al., 2021; Stacey et al., 2025). Figure 1.1 illustrates this complex industrial context.

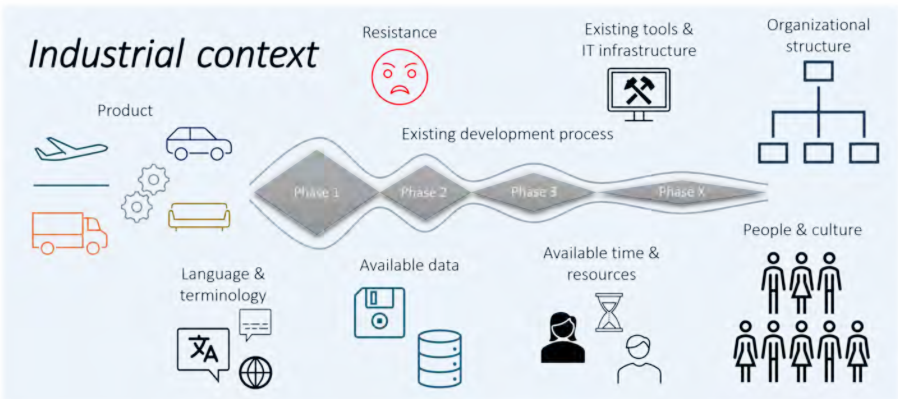


Figure 1.1: Figurative depiction of aspects that influence the industrial context in which new design methods need to fit.

At the same time, adhering to method criteria such as 'easier to use', 'less time-consuming', and alignment with *status quo* must be treated with caution, considering the radical changes required to align with sustainable production and consumption (e.g., Bengtsson et al., 2018; Ceschin and Gaziulusoy, 2019). This 'dilemma' is illustrated in Figure 1.2 by a design researcher who holds a view of an ideal way to practice design and pushes for this change from one side. On the other side, the time-pressured designer pushes to maintain as much of the *status quo* as possible. In practice, it is not straightforward how to approach such a situation.

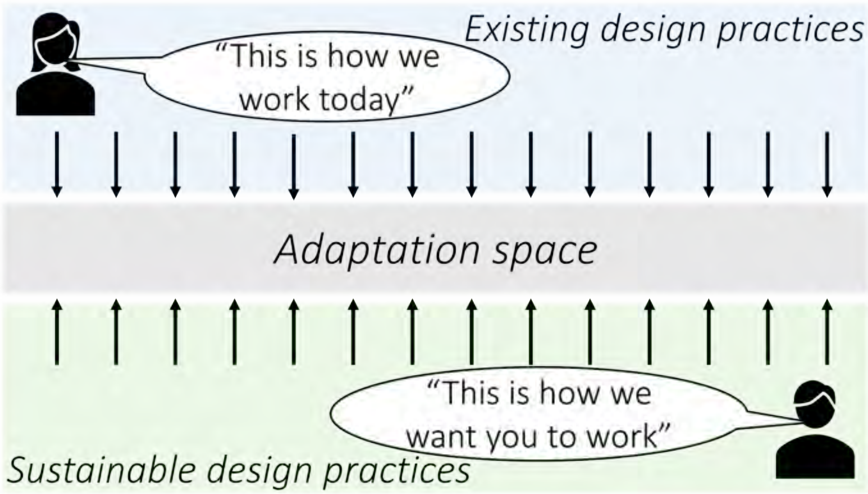


Figure 1.2: Dilemma where the design researcher pushes for an ideal way in how to practice design, where the time-pressured designer desires as little change as possible.

Furthermore, while there are several enablers that have been proposed in the 'design domain', it is evident that the 'managerial' side of industrial adoption, or *change* requires more attention (e.g., Geis et al., 2008; López-Mesa and Bylund, 2011; Booker, 2012; Jagtap et al., 2014; Pieroni et al., 2019), and there is research in the 'design domain' that has sought to better integrate such organizational and human-behavioral perspectives of *change* (e.g., Faludi et al., 2020; Boucher et al., 2018; Gould, 2018; Brones et al., 2017; Boks, 2006; Johansson, 2002; Ritzén and Beskow, 2001). Nevertheless, although many studies have addressed the industrial adoption of design methods from different perspectives, the issue remains a contemporary concern that continues to receive attention (e.g., Faludi et al., 2020; Vilochani et al., 2024; Vicente and Camocho, 2024; Stacey et al., 2025) and thus remains a research topic of interest. In parallel, the social phenomenon of change, or resistance to change, and how to manage change, has been acknowledged and thoroughly treated in 'management literature' for more than 75 years (e.g., Lewin, 1946; Samuelson and Zeckhauser, 1988; Kotter, 1995; Burnes, 2015). Here, a vast body of knowledge exists to better understand why many of the identified issues arise and how industrial adoption of design methods can be facilitated.

To summarize, the research problem can be formulated as follows:

- The industrial adoption of design methods has been thoroughly studied in the design domain, where several barriers and enablers have been proposed. However, the industrial adoption remains a contemporary problem that can be better understood and is in need of practical guidance.

At the same time, the body of knowledge in the management domain can be used to better understand why this issue persists and to strengthen theoretical and practical contributions, thereby advancing research on this topic. This thesis, therefore, adopts an interdisciplinary scope, in which different perspectives typically scattered across domains will be considered. This is figuratively illustrated in Figure 1.3. In turn, this aims to contribute new knowledge relevant to the industrial adoption of design methods, benefiting the field of sustainable design and the design research community.

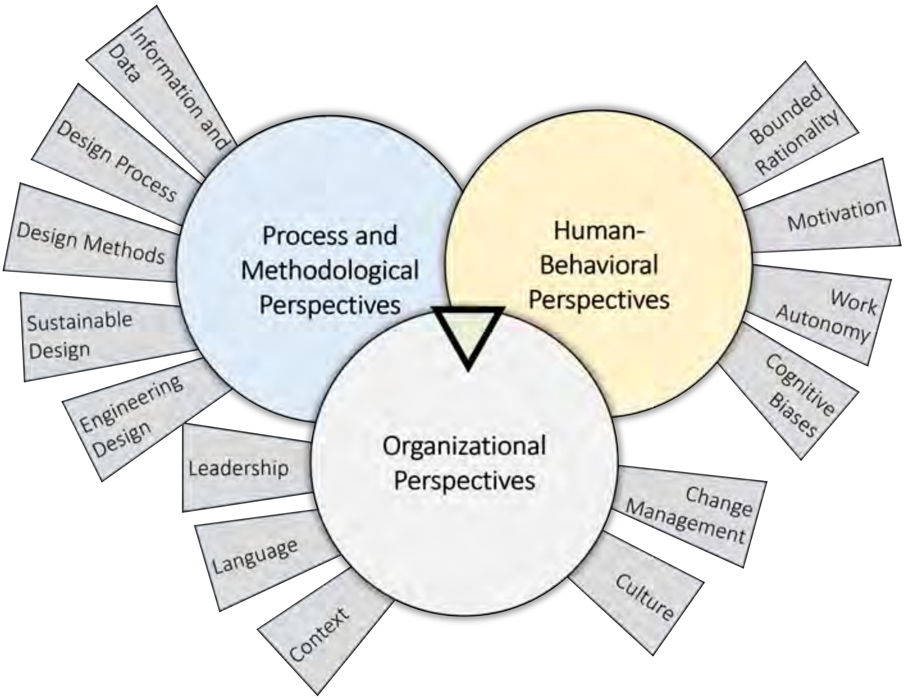


Figure 1.3: Illustration of the interdisciplinary scope of this research. The large circles represent the three perspectives to consider, each of which may employ different theories and concepts. The green triangle illustrates how these perspectives, when considered simultaneously, can provide a better understanding of and facilitate the industrial adoption of design methods.

1.4 Research aim and questions

This research aims to deepen understanding of what can limit adoption, how to facilitate it, and how design methods can enhance an organization's ability to design more sustainable solutions. Three research questions are formulated to guide this research and to structure the findings and contributions of this thesis.

- RQ1: *What barriers influence the industrial adoption of new design methods for sustainable design?*

RQ1 aims to generate new insights into the key barriers to industrial adoption. The research question is intentionally broad to reflect the exploratory and interdisciplinary scope of this research. It can thus capture and synthesize previously raised barriers scattered across domains that remain challenging, as well as raise unprecedented barriers.

- RQ2: *In what ways can new design methods support manufacturing companies in their sustainability transition?*

RQ2 is formulated on the assumption that industrial adoption is challenging. In turn, this research question seeks to capture how design methods, potentially beyond industrial adoption, can support manufacturing companies in their sustainability transition.

- RQ3: *How can the industrial adoption of new design methods for sustainable design be facilitated?*

RQ3 aims to identify different means of facilitating[3] industrial adoption of new design methods. This can include insights and recommendations that aid adoption of the new design methods, as well as practical guidance that more directly supports industrial adoption. Moreover, this question involves evaluating any practical guidance to further clarify how it facilitates adoption in practice. The research question is intentionally broad to reflect the exploratory and interdisciplinary scope of this research.

1.5 Research setting and logic

This research has been conducted across diverse settings and comprises four main studies. The overarching research logic is presented in Figure 1.4. At the top, the research projects that have provided the setting for the studies are illustrated in chronological order. In the middle, the author's separate studies conducted within these projects are illustrated, highlighting how they build on one another. Moreover, different colors are also used to show how the studies relate to the appended papers. These are illustrated at the bottom, and how they build on each other.

[3]Facilitating is here defined as "to make something possible or easier" (Cambridge, 2026a).

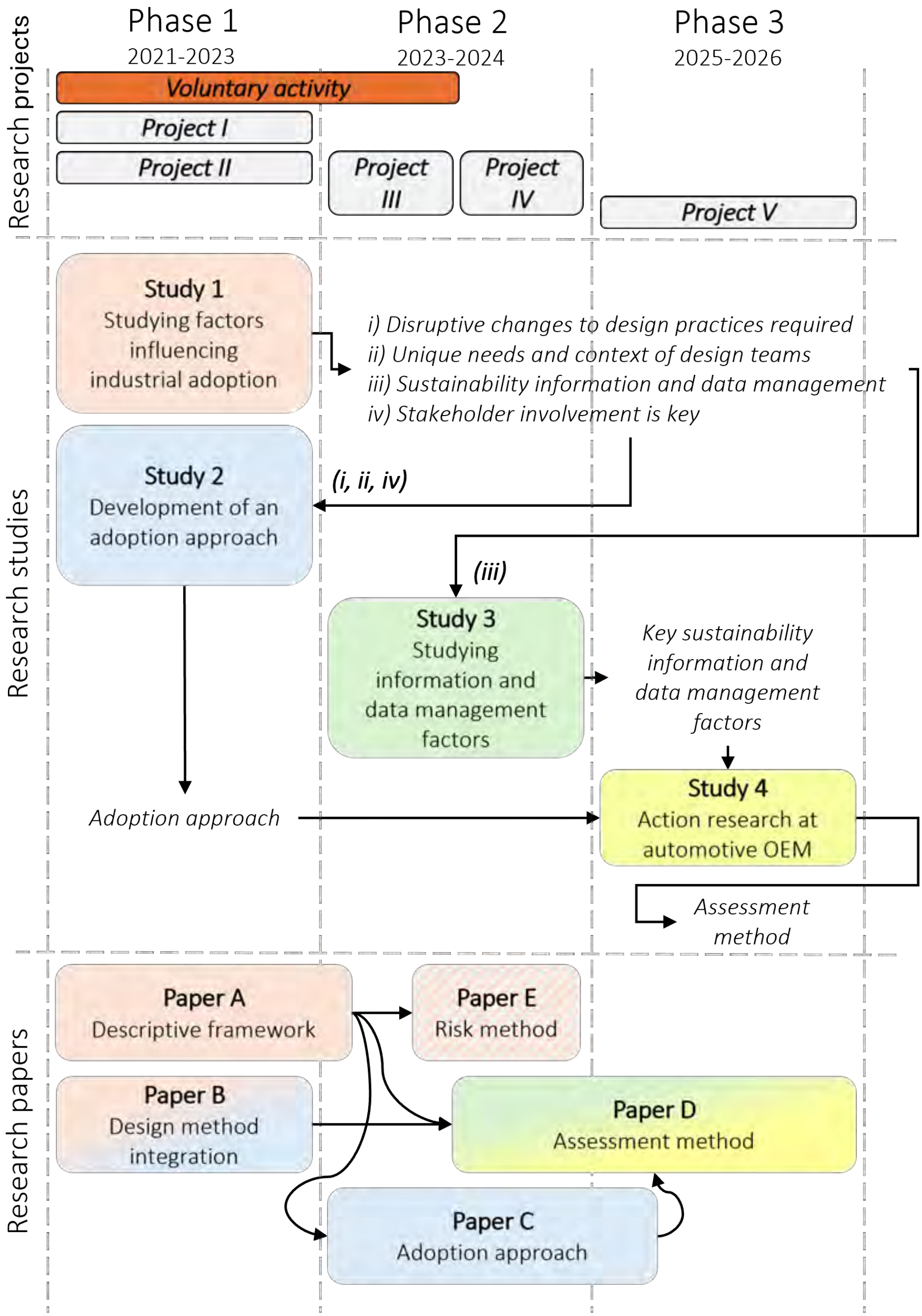


Figure 1.4: Overarching research logic illustrating how separate research studies (denoted as 1-4) relate to research projects (denoted as I-V), and how these in turn are disseminated in five separate research papers (denoted as A-E). i-iv refers to the sub-themes that emerged from Study 1 and guided the continued work in this thesis.

Study 1 explored factors influencing industrial adoption, and early empirical data collection and literature analysis led to this research's interdisciplinary scope. From this, sub-themes emerged which guided the subsequent work. **Study 2** was used to develop an adoption approach by drawing on the main findings of Study 1. **Study 3** elaborated on the findings from Study 1 by specifically studying factors related to the management of sustainability information and data. **Study 4** elaborated on the outcomes from Studies 2 and 3 at an automotive OEM, using action research to apply and evaluate an adoption approach and an assessment method. The research projects that have supported this research are presented below, along with clarification of how they supported the separate studies. The appended papers will be described in detail in the following sections.

Project I - Digital Sustainability Implementation Package: This was a Vinnova-funded research project (Vinnova, 2020b), with the overall purpose to enable a strategic sustainability perspective early in the product innovation process. The project included two research groups that develop and propose design methods: *Systems Engineering Design* at Chalmers University of Technology, and Strategic Sustainable Development at Blekinge Institute of Technology. The project involved several actors from the manufacturing industry (Volvo Group, GKN Aerospace, Roxtext, IKEA, Dynapac, Volvo Construction Equipment, and Tetra Pak), two large product development consulting companies (AFRY, TogetherTech), and a digital solution provider (Eurostep). The project period spanned from April 2021 to February 2023, and provided the author with a platform to study the industrial adoption of design methods and develop an adoption approach (Studies 1 and 2). The results were later used as input to Studies 3 and 4.

Project II - Demonstration of Infrastructure for Digitalization enabling industrialization of Additive Manufacturing: This was a Vinnova-funded research project (Vinnova, 2020a), and the overarching purpose was to achieve efficient management of information and data in additive manufacturing for complex value chains. The project included several research groups that develop and propose design methods: *Systems Engineering Design* and *Powder Metallurgy and Additive Manufacturing* at Chalmers University of Technology, as well as research groups focusing on additive manufacturing at RISE (Research Institutes of Sweden). The project involved several actors from the manufacturing industry (Volvo Group, Volvo Construction Equipment, Epiroc, Uddeholm, Brogren Industries AB), and a digital solution provider (Eurostep). The project period spanned from April 2021 to May 2023 and provided the author with a platform to study the industrial adoption of computerized design methods for additive manufacturing. The results were used to generalize the findings in Studies 1 and 2, and later used as input to Studies 3 and 4.

Project III - Designing the Impact of Digital Product Passport: This was a Vinnova-funded research project (Vinnova, 2022), and the overarching purpose was to prepare the automotive industry to meet the changing conditions expected through the EU´s Green Deal and New Circular Economy Plan, and Digital Product Passport. The project included two research groups that develop and propose design methods: *Systems Engineering Design* at Chalmers University of Technology and *Strategic Sustainable Development* at Blekinge Institute of Technology. The project also involved several actors across the automotive value chain, but Volvo Group was the key partner. The project period spanned from January 2023 to August 2023, and provided the author with a platform to study barriers and enablers from a sustainability information and data management perspective (Study 3). The results were later used as input for Study 4.

Project IV - Circular and Data Driven Collaborative Design Framework: This was a Vinnova-funded research project (Vinnova, 2023), and the overarching purpose was to prepare the automotive industry for co-developed circular solutions, making use of the transparency and traceability of sustainability information and data throughout the product life cycle and value chain. The project included one research group that develops and proposes design methods: *Systems Engineering Design* at Chalmers University of Technology. The project also involved various actors across the automotive value chain, but Volvo Group was the key partner. The period spanned from December 2023 to August 2024 and provided the author with a platform to study barriers and enablers from a sustainability information and data management perspective (Study 3). The results were later used as input for Study 4.

Project V - Sustainable Materials Data Ecosystem: This was a Vinnova-funded research project (Vinnova, 2024b), and the overarching purpose was to increase transparency and accelerate the introduction of new and more sustainable materials in the automotive value chain. The project included one research group that develops and proposes design methods: *Systems Engineering Design* at Chalmers University of Technology, and one research group that develops material behavior models, the *Division of Engineering Materials* at Linköping University. The project involved several actors from the automotive value chain (Volvo Group, SSAB, Stena Aluminum, Borealis, K.D. Feddersen, Polykemi, and Juteborg), as well as AI Sweden at Lindholmen Science Park. The project period spanned from February 2025 to December 2026, and provided the author with a platform for doing action research to develop and test practical support (Study 4).

Voluntary activity at Engineers Without Borders-Sweden (EWB-SWE): This is a Swedish humanitarian engineering non-governmental organization (NGO) with 500+ volunteering members working on sustainable development (Engineers Without Borders Sweden, 2026). EWB-SWE, for example, carries out international projects across several low-income countries, as EWB-SWE phrases it, *humanitarian engineering.* These efforts typically involve multidisciplinary projects trying to introduce new technologies in low-income contexts to (i) empower local communities, and (ii) increase their social welfare. A non-paid collaboration between EWB-SWE and the author was initiated to support EWB-SWE's efforts and contribute to sustainable development. The collaboration began in April 2022 and continued until June 2024, encompassing both internal improvement projects and online and on-site activities. This collaboration provided the author with a platform to study the industrial adoption of design methods within a humanitarian engineering NGO. The results were later used to generalize the findings of this thesis.

1.6 Scope and delimitations

There are five delimitations that need to be listed to clarify the scope of this thesis.

- This research has predominantly involved companies representing the manufacturing industry. However, this is not because other sectors are out of scope, but because of the available research settings. Moreover, the findings from this research are thus considered relevant to other sectors working towards sustainable design, where readers from, e.g., construction and fashion, can also benefit from this thesis.
- The interdisciplinary scope of this research was predominantly governed by the research settings, which focused on collecting large empirical samples rather than identifying a problem through a systematic literature review.
- This research incorporates managerial perspectives to the extent that established theories are used to better understand and explain industrial adoption of design methods. However, this thesis does not aim to contribute new knowledge to the field of management studies.
- The design methods utilized in this thesis to study industrial adoption have been developed, evaluated, and disseminated before this research. This thesis thus relies on the assumption that the industrial adoption of these design methods contributes to the development of sustainable solutions. Therefore, it is not within the scope of this thesis to further assess or evaluate how each of these design methods performs in meeting their specific goals.
- In line with this, this research does not advance the underlying logic and elements of the design methods studied; rather, it aims to contribute knowledge that clarifies why the industrial adoption of design methods can be challenging yet also facilitated and improved.

1.7 Thesis outline

This chapter has briefly introduced the reader to the problem and focus of this research. Chapter 2 outlines the research methodology adopted in this research. Chapter 3 presents the frame of reference. Chapter 4 presents the main findings from the appended papers that contribute to this thesis. Chapter 5 presents the main contributions of this thesis. Chapter 6 discusses the results of this thesis with respect to the RQs and their validity. Chapter 7 concludes the main findings and presents the way forward. Lastly, the reference list is provided, followed by the appendices and the papers on which this research is based.

Chapter 2

Research methodology

This chapter presents the overall research methodology, clarifying the research structure, the study objects, and the different methods used to collect and analyze data across the separate research studies. Aspects of epistemology, validity, and ethical considerations will also be presented.

2.1 Research on *design*

Research on the design activity is commonly referred to as either *design research* (e.g., Blessing and Chakrabarti, 2009; Gericke et al., 2022), and/or occasionally *design science* (e.g., Fuller, 1957; Gregory, 1966; P. Y. Papalambros, 2015), and finds itself in the intersection between both natural sciences and social sciences. Doing design commonly involves scientific and engineering knowledge, whereas the design activity is a human act (Willem, 1990; Pahl et al., 1996; Cross, 1999). *Design research* focuses on both understanding and supporting the design process, striving to contribute new knowledge relevant to improving this activity (Blessing and Chakrabarti, 2009; Säfsten and Gustavsson, 2020). The dominating view of how to 'best' carry out design has changed over time since the first conference on design methods in 1962 (Cross, 2007). Gregory (1966) summarized *design science* as.

> "Design science is concerned with the study, investigation and accumulation of knowledge about the design process and its constituent operations. It aims to collect, organize and improve those aspects of thought and information which are available concerning design and to specify and carry out research in those areas of design which are likely to be of value to practical designers and design organizations."

Similarly, Papalambros et al. (2025), roughly 60 years later elaborate on *design science*:

> "Design is how we humans change the world. We do this by creating artifacts – products, services and systems. Design Science

is the discipline that studies the creation of artifacts – products, services and systems and their embedding in our physical, virtual, psychological, economic and social environments."

Blessing and Chakrabarti (2009) claim that the overall goal of design research is "to make design more effective and efficient, in order to enable design practice to develop more successful products". Altogether, this supports highlighting the relevance of contributing new knowledge to the topic of industrial adoption of design methods, which aligns with the overarching goal of design research, and justifies the interdisciplinary scope. An interpretation of such research is visualized in Figure 2.1.

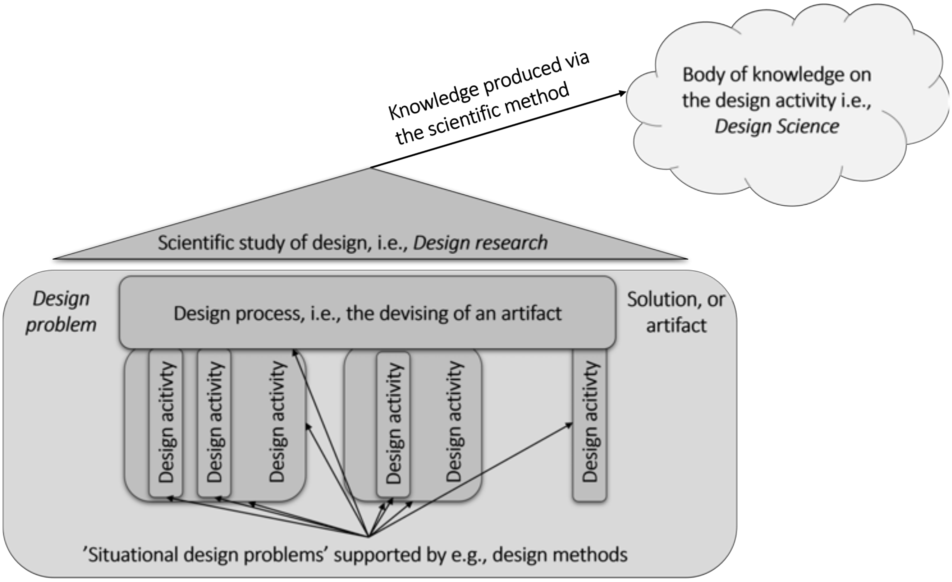


Figure 2.1: Interpretation of how a scientific study of the design activity leads to a body of knowledge to better understand *design*.

2.2 Study objects

The study objects in this research have been purposefully sampled to align with the purpose and objectives of the individual studies and, to some extent, with availability (Eisenhardt, 1989; Flick, 2007; Cash et al., 2022). There are four main study objects across the studies in this research, which are described in general below, and more specifically per study in Section 2.3.

First, **design methods**, which can be seen as socio-technical constructs as described by Gericke et al. (2022):

> "The engineers applying the method are as much part of the system as the descriptions of the method, or the diagrams, models and

> documents they read and construct. What happens depends on the interaction of all the elements of the system: engineers interpreting the description of the method, using software systems, reading diagrams, passing on documents to their colleagues."

Thus, although design methods play an essential role in design, the design method, as such, does not act on its own but derives its value through interaction with designers in a socio-technical interplay.[1] Moreover, this emphasizes the need to consider the context in which the design methods are to be adopted, as well as the individuals involved. Furthermore, several design methods have been used in this research and have predominantly been developed by the two research groups, i.e., *Systems Engineering Design* (SED) at Chalmers University of Technology and *Sustainable Product Development* (SPD) at Blekinge Institute of Technology. These design methods were deemed as appropriate candidates since they: (i) have been developed and evaluated together with industry; (ii) have been externally assessed and peer-reviewed; (iii) appropriately represent the process and methodological context of *sustainable design*; and (iv) were available for use in the research projects. Furthermore, what constitutes any *design method* as a construct or artifact will be further described in Section 3, as well as the two categories of design methods, i.e., SED and SPD.

Second, the **manufacturing companies** also serve as study objects, and represent the manufacturing industry. These organizations have, for example, been represented and understood through documents that capture their expressed values, formal processes, and tools. Furthermore, the organizations in this research are also represented by the designers as a collective. This can, for example, relate to patterns in what designers from the same organization say about their organization, e.g., that designers are generally occupied here, or how sustainability is treated. All companies taking part in this research align with the following two criteria: (i) an international company acting in the manufacturing industry; and (ii) has an expressed ambition to contribute to sustainable production and consumption.

Third, the practitioners, referred to as **designers** and **design teams**, within manufacturing companies are among the main study objects since they are often the users, or at least involved in the use, of design methods. Therefore, they represent the individuals who interact with the design methods and their organization from their perspectives, providing insights, e.g., on their unique organizational context. The practitioners taking part in this research have been selected on a case-by-case basis, as needs have differed depending on, e.g., the design method to be used. However, all designers are employed by the case companies.

[1]The author wishes to emphasize that advances in artificial intelligence (AI) and its use in design can possibly influence this relation and interplay. However, this research was conducted amid the 2023 AI boom and has not investigated its potential impact. There is ongoing research looking into the role of AI and design tools (e.g., Gomez et al., 2025; Woofter et al., 2026.

Lastly, **design researchers** are also treated as study objects in this research, who typically act in two roles: (i) *method developers*, i.e., the ones that have developed the design method; and (ii) often as the role of *method experts*, i.e., an individual considered an expert in using the design method. However, although it is not necessarily design researchers who need to take on the role of *method experts*, they did so in many instances. This was the case when the design methods were completely new to the organizations, meaning there were no *method experts* available internally.

2.3 Research design

This research adopts a qualitative approach (Creswell, 2014) comprising four main studies, each employing a combination of different methods for data collection and analysis. The intent is to explore industrial adoption of design methods from all three perspectives, i.e., process and methodological, organizational, and human-behavioral. Moreover, to provide structure among these separate research studies, the *Design Research Methodology* (Blessing & Chakrabarti, 2009) (DRM) is used, as it is effective for visualizing and positioning the research studies (1-4) relative to one another, and what type of contribution they have to this thesis. This is illustrated in Figure 2.2.

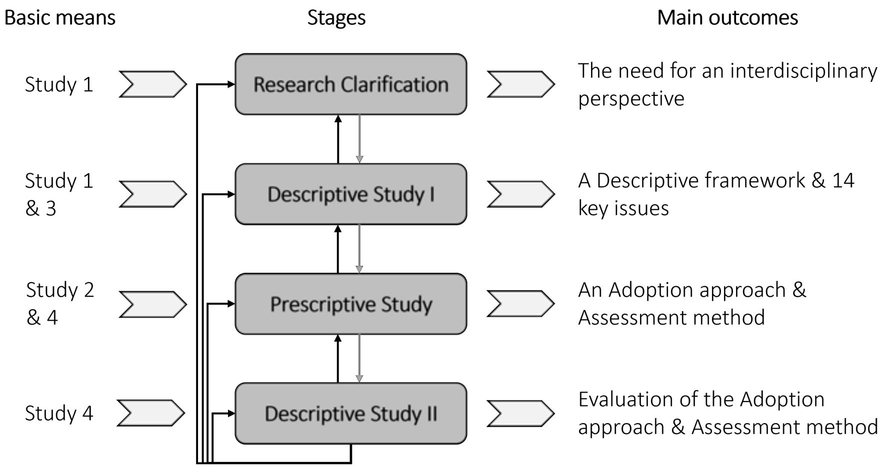


Figure 2.2: The research structure of this research visualized according to the *Design Research Methodology* (Blessing & Chakrabarti, 2009).

Furthermore, the main findings from Studies 1-4 relevant to this thesis are reported on in five appended papers, and contribute to the formulated research questions in different ways, as seen in Table 2.1.

Paper A presents the main results from Study 1, a descriptive framework with 53 interdisciplinary factors influencing the industrial adoption of design methods, and a conceptual model. Furthermore, the findings are compared with interdisciplinary literature to explain and clarify them, resulting in *systemic* *barriers* and propositions easier to address in isolation. In turn, providing answers to RQ1 and RQ2, and partly to RQ3.

Paper B presents a selected set of results from Studies 1 and 2, in which the potential of integrating one SPD with one SED design method is explored. In turn, providing answers to RQ1 and, to some extent, to RQ2 and RQ3.

Paper C presents the main results from Study 2, a needs-driven and collaboration-based approach that facilitates the industrial adoption of design methods. In turn, providing answers to RQ3 and, to some extent, to RQ1.

Paper D presents the main results from Studies 3 and 4, a contextually adapted assessment method that guides the assessment of a collaborative ecosystem's ability to share and manage sustainability information and data. In turn, providing answers to RQ1 and RQ3, and partly to RQ2.

Paper E presents the development and testing of a risk-assessment method as part of Project II. It leverages parts of the approach developed in Study 2, but in the context of additive manufacturing, while addressing key challenges identified in Study 1. In turn, this supports generalizing the answers to RQ1 and RQ3 beyond the context of sustainable design, i.e., to additive manufacturing.

Table 2.1: Paper A-E's contribution to the RQs. Upper case X = significantly contributing to RQ. Lower case x = partly contributing to RQ. O/o = contributing to RQ1/RQ3 but in the context of additive manufacturing.

Papers / *Research questions*	Paper A	Paper B	Paper C	Paper D	Paper E
RQ1: What barriers influence the industrial adoption of new design methods for sustainable design?	X	X	x	X	O
RQ2: In what ways can new design methods support manufacturing companies in their sustainability transition?	X	x		x	
RQ3: How can the industrial adoption of new design methods for sustainable design be facilitated?	x	x	X	X	o

To provide transparency on how each of the separate studies was conducted, they are described thoroughly in the sub-sections below.

2.3.1 Study 1: Exploring factors influencing the industrial adoption of new design methods

Study 1 was the primary contributor to the two initial stages of DRM, and Project I was the primary source of empirical data. Here, a combination of *Participant Observation* and a *Multiple Case Study* (Säfsten & Gustavsson, 2020) was used to collect qualitative data, which was later analyzed using *Glaserian Grounded Theory* (Charmaz, 1996; Walker and Myrick, 2006).

2.3.1.1 Participant observation in a multiple case study

Empirical data collection was primarily conducted in Project I, as it best aligned with the sustainability focus of this research. However, empirical data were occasionally collected in Project II and EWB-SWE to improve the generalizability of the findings. The researcher, nevertheless, participated in several activities within Project I, serving as a coordinator responsible for coordinating interactions between designers and design researchers. In turn, this enabled the researcher to study the interaction between designers, *method developers* and *method experts*. Moreover, the researcher did not directly influence the responses or actions aimed to be captured in Study 1, but mediated and facilitated many of the activities. To give an idea of how this interaction appeared in practice, two figurative examples of these activities are illustrated in Figure 2.3.

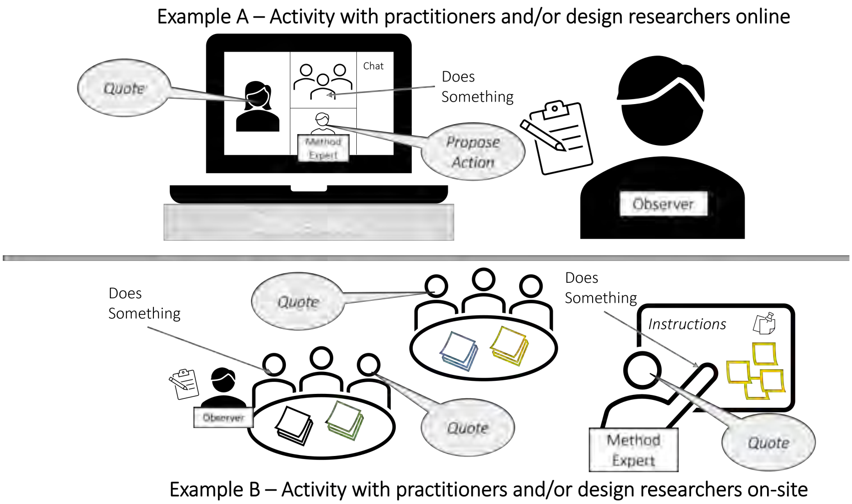


Figure 2.3: Figurative examples of scenarios illustrating how data was collected using observations.

This approach aligns with what Säfsten and Gustavsson (2020) refer to as *participant observation*. The approach can more specifically be classified as *moderate participation*, which relates to the degree of interaction: "The observer balances between being an insider and an outsider, between participation and observation". The observations are *direct* and *unstructured* (Säfsten & Gustavsson, 2020), and were collected as qualitative observations (Creswell, 2014), with codes recorded in notebooks in an *in vivo format* (Miles et al., 2014). Figure 2.4 illustrates the collected data and shows how it captures all three perspectives; this example yielded six distinct codes.

Data were collected over almost two years in Project I alone and yielded roughly five full notebooks, each containing 192 A5 pages of qualitative data.

The collected data captured aspects relevant to the topic and included both process and methodological, organizational, and human-behavioral aspects, as shown in Figure 2.4. The collected data can, in turn, be distinguished into four different categories:

- Quotes either from a researcher or a designer.
- Observations of concrete events by either a researcher and/or a designer.
- Notes of something that a researcher or designer said or presented, but not captured how it was explicitly phrased, and is therefore separated from quotes. It also relates to assigned 'action points' by a researcher or designer.
- Reactions, which is the observer's reaction to either of the above, resulting in either a 'thought' or 'idea' related to the topic that is studied.

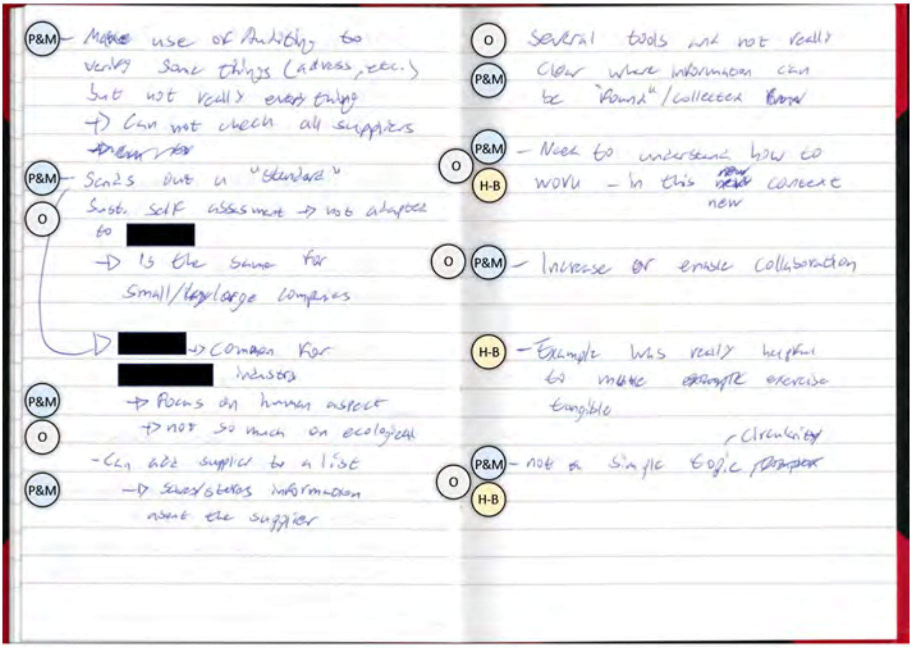


Figure 2.4: Example of raw data captured in a notebook during an informal meeting with a designer. Blue circles represent codes that capture a process and methodological perspective (P&M). Yellow circles represent codes that capture a human-behavioral perspective (H-B). White circles represent codes that capture an organizational perspective (O).

Several different activities in Project I resulted in the possibility of collecting empirical data. A multiple-case study approach (Säfsten & Gustavsson, 2020) using three companies from Project I served as the primary data collection method. The case studies are summarized in Table 2.2 on the next page.

All activities involving participant observation in Project I are listed and summarized below.

- A total of 30 workshops carried out across the six case studies, and corresponded to the appropriate use of many of the proposed design methods, as they were briefly described in Section 3.
- More than 20 recurring bi-weekly meetings varying between 30 and 45 minutes with the case companies. These were used to coordinate the activities carried out in the case studies. For example, ensuring that relevant industrial participants took part in the workshops or that the required data and information were available during them. These meetings also commonly involved designers elaborating on the issues they face and the opportunities they see for their organization's sustainability transition. For example, 'there is a lack of time', and 'that sustainability is gaining traction inside the organization'.
- More than ten internal meetings were carried out with one or more design researchers, or *method experts*. These were used to coordinate and prepare the use of the design methods in the case studies. For example, activities that consolidate results from the workshops or activities related to adapting the design methods.
- Four seminars were carried out in Project I with the full project consortium. The seminars lasted five to ten hours and included focused group discussions on emerging topics related to the study.

Additionally, more than ten questionnaires were also sent out in Project I. This was done either during the seminars or in preparation for them to obtain individual designer responses to the topics discussed. The questionnaires mixed free-form questions with quantitative questions

Three companies from Project I were used in the case studies.

Company A is a large manufacturer of integrated metallic and composite assemblies for aero-structures and aero-engine products. Two case studies were carried out with Company A, both focusing on the sustainable industrialization of additive manufacturing. The cases had different scopes and were conducted in different functions within the organization, but both were in the context of technology integration and development.

Company B is a semi-large manufacturer of sealing solutions for the telecom, manufacturing, and construction industries. This case focused on sustainability governance and on integrating sustainability into their product innovation process, using a steel frame as the case product.

Company C is a large manufacturer in the automotive sector. Three cases were conducted with this company, but two involved several joint activities, namely cases C1 and C2 (see Table 2.2). The scope of these was deemed aligned, and tighter collaboration between the two business units, i.e., *product design* and *procurement & sourcing*, was also considered necessary. This required participants from several functions, since product design and procurement &

sourcing are treated as separate business units within the same company. The third case from this company came from a third business unit and was treated as a separate case study.

Table 2.2: Summary of the multiple case studies in Study 1.

Case & Company	*Context*	*Design scope*	*Conducted workshops*	*Nr. of different SED methods applied*	*Nr. of different SPD methods applied*
A1	Technology integration and development	Sustainable design of a turbine rear structure using laser powder bed fusion	2 separate, and 2 joint with A2	1	3
A2	Technology integration and development	Sustainable repair of a fan blade with direct energy deposition	2 separate, and 2 joint with A1	-	3
B1	Management and product design	Strategically integrating sustainability in the product innovation process of a steel frame	8 separate	-	5
C1	Product design	Sustainable and circular design of a seat in the new generation of electric vehicles	10 joint with C2, and 1 joint with C2 and C3	3	6
C2	Procurement and sourcing	Sustainable and circular supply chains for a seat in the new generation of electric vehicles	1 separate, 10 joint with C1, 1 joint with C1 and C3	3	6
C3	Material and product design	Sustainable material selection for a cable bracket component	7 separate, and 1 joint with C1 and C2	1	3

Six case studies were carried out in total as part of Study 1, illustrated in Table 2.2, and each of the six cases involved more than 10 different industrial participants and five different design researchers. It is difficult to claim what is a suitable number of cases; however, six is generally considered sufficient (Eisenhardt, 1989). Moreover, the case studies were purposefully sampled and designed to generate knowledge about the industrial adoption of design methods (Eisenhardt, 1989; Flick, 2007; Cash et al., 2022).

2.3.1.2 Glaserian Grounded Theory analysis

The empirical data were analyzed using *Glaserian Grounded Theory* analysis (Charmaz, 1996; Walker and Myrick, 2006) to inductively identify interdisciplinary factors that influence the industrial adoption of design methods, capturing them within a descriptive framework, which is later compared with previous literature to further clarify and explain the empirical findings. *Glaserian Grounded Theory* was predominantly chosen because it draws on elements of *interpretative* and *positivist* assumptions and has a strong history in qualitative research (Charmaz, 1996), and thus aligns with the scope and aim of this research, as it allows both diverse and novel themes to emerge and further strengthens the exploratory and interdisciplinary scope. *Glaserian Grounded Theory* analysis consists of three main analytical steps: *open coding*; *selective coding*; and *theoretical coding*, and the outcomes are later compared to existing theories. The overall process is visualized in Figure 2.5, on the next page. As illustrated, only data from Cases C1 and C2 were used for the first two steps, whereas data from the remaining cases were used in the third step.

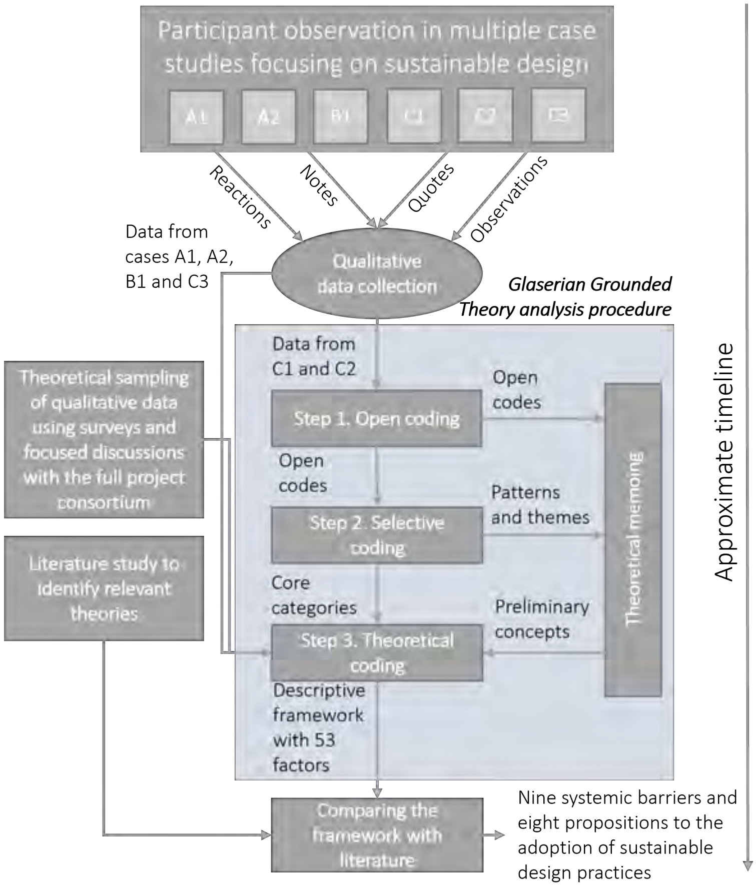


Figure 2.5: Analysis procedure of the collected empirical data in Study 1.

Step one: *Open codes* were assigned based on the raw data captured in the notebooks. The three guiding criteria were used to steer this process and ensure that epistemological considerations were appropriately maintained, and the background to these will be described in the next sub-section.

1. The codes correspond to the data. This criterion focused on adopting the *positivist* tradition and adds a dimension of correspondence (Åge, 2011), i.e., the assigned meaning or code should correspond to the collected data.

2. The data is interpreted and understood in its context when assigned codes. This criterion focuses on adopting a *hermeneutic* tradition and adds a dimension of understanding, ensuring the *interpretative* assumptions (Åge, 2011), i.e., that the collected data be interpreted and understood in their context when assigned meaning or codes.

3. The codes are useful. This criterion was adopted to limit data collection and add a dimension of usefulness, aligning with the *pragmatism* tradition (Åge, 2011). The collected data or assigned meaning should be useful to the studied topic. This strategy was added to prevent data collection from spiraling out of control due to the wide scope of this research (Eisenhardt, 1989; Walker and Myrick, 2006).

Step two: Selective coding later strived to find patterns and themes, and these are referred to as *core categories*. **Step three:** Theoretical coding focused on generating a theory grounded in the empirical data, which in turn conceptualizes and frames how the *open codes* and *core categories* relate to each other (Walker & Myrick, 2006). Moreover, *theoretical memos* were continuously formulated throughout the open and selective coding process, as visualized in Figure 2.5. Such memos refer to preliminary ideas or sub-concepts captured as short sentences that saturate and converge over time (Walker & Myrick, 2006). Furthermore, data from the remaining cases were included in this step:

- Clarify the *core categories* and the additional relations between them.

- Strengthen the *core categories* and the identified relations.

- Add further depth to the *core categories* and the relations.

Charmaz (1996) refers to this step as theoretical sampling, i.e., "collecting more data to clarify your ideas and to plan how to fit them together". Table 2.3 provides an example of how the raw data is assigned *open codes*, and later placed in more abstract *core categories* (i.e., selective codes).

The final step of the analysis examines how the findings compare with and relate to the literature (Charmaz, 1996). This step added further nuance and depth to the empirical findings by comparing them with the interdisciplinary literature, identified through a Snowballing approach (Wohlin, 2014). The focus was to identify literature that can further explain and clarify the empirical findings by bridging domains and framing the industrial adoption of design methods from all three perspectives (i.e., process and methodology, organization, and human behavior). This analysis, in turn, resulted in a set of *systemic barriers* and propositions in Paper A. The intention was to make the empirical findings, as framed by the 53 factors in the descriptive framework, easier to absorb and manage to guide both research and practice on what actions and pressing issues need to be addressed.

Table 2.3: Example of analyzing the qualitative empirical data.

Context	*Note*	*Open coding*	*Selective coding*
Informal meeting with company C - Procurement and sourcing	Practitioner: *Need to work in new ecosystem to work "circular" *See a need of a new system *Various of different new issues "1000's" *Traceability, several actors -> need to ensure "waste" is managed -> How do we even start this collaboration	There is a need to collaborate with actors differently to develop more sustainable solutions	New sustainable design practices
Context	*Note*	*Open coding*	*Selective coding*
WS at company C where they present the case product for C1 and C2	Development of product -Product breakdown -> different view -Core structure *Comfort system *Safety system *Custom specific -Product one of the most complex parts *Legal *Safety *Integrate many things -Scalable	There is a need for researchers to understand the case product	Method experts' understanding of company case and context

2.3.1.3 Research validity in Study 1

Ensuring the validity and reliability of the findings in qualitative data analysis is generally important, and several strategies can be used (Creswell, 2014; Säfsten and Gustavsson, 2020). Some of the *tactics* proposed by Miles et al. (2014) are 'by default' incorporated into the *Glaserian Grounded Theory* process for analyzing the data.

- *Seeing Plausibility* by working bottom-up, or inductively, from the raw data to *open coding.*
- *Noting patterns and themes* and *Clustering* through *selective coding.*
- *Noting the relations between variables* and *Making conceptual coherence* via the *theoretical coding.*
- *Counting* by manually counting the occurrence of *open codes* in each *core category.*

Several additional strategies have also been used to further strengthen the validity.

- The three criteria used to ensure correspondence, understanding & interpretation, and usefulness during the data collection and analysis procedure.
- *Triangulation* (Creswell, 2014; Eisenhardt, 1989) by using a multiple-case study approach and different data collection methods within this context. This is further supported by two additional empirical contexts (Project II and EWB-SWE), which strengthen the external validity of the findings.
- *Peer debriefing* (Creswell, 2014) by involving peers who have checked the coding and also been involved in discussing the results.
- Clarifying the bias of the researcher (Creswell, 2014).
- Comparing the findings to previous studies to further strengthen the validity (Säfsten & Gustavsson, 2020).

Ensuring reliability in Study 1 was challenging because, for the most part, a single researcher (i.e., the author of this thesis) collected and analyzed the data. Furthermore, incorporating elements of *hermeneutics* and *pragmatism* also influences the reliability of this research. Transparency in the documentation of collected data and analysis has been one approach to counter this, as it enables external scrutiny of the procedure and the ability to revisit the raw data. Moreover, there is also transparency regarding the researcher's interactions with the study objects. *Peer debriefing* also supports improving the *inter-rater reliability* of the findings (Säfsten & Gustavsson, 2020).

Furthermore, it is relevant to acknowledge the researcher's bias and its potential influence on this research. Both in the sense that the researcher determines what is considered *useful*, and occasionally *interprets* what is happening, directly influencing the results. Two main aspects are important to give an account of: First, the author had no prior knowledge of the design methods used in this research, but had an academic background in mechanical engineering and design, with a particular interest in sustainability, complemented by higher-education courses in business administration, and prior knowledge in this field can influence what is considered useful. Second, the adopted lens towards *sustainable design* will be described in Section 3 as it can influence the interpretation of the collected data. Aspects of validity will be revisited in Section 6.4.

2.3.2 Study 2: Development of an adoption approach

In parallel to Study 1, Study 2 had a strict prescriptive focus, aiming to develop and test practical guidance to facilitate the industrial adoption of design methods. In practice, this was done by incorporating the key findings iteratively to develop ways to address the identified problems and barriers, which is best described as an *abductive process* (Säfsten and Gustavsson, 2020; Dorst, 2011), since new learnings and insights from Study 1 were continuously captured and used to both improve and further formalize the approach. More specifically, in parallel with the case studies, the researchers continuously reflected on and documented the sequence of activities conducted with the designers, enabling them to generalize and formalize the findings into an adoption approach while accounting for the researchers' role (treated as *method experts*). The development process followed iterations of: (i) conceptualization; (ii) embodiment in PowerPoint; and (iii) testing and evaluation in the subsequent meetings, and across the case studies. The overarching research methodology is illustrated in Figure 2.6.

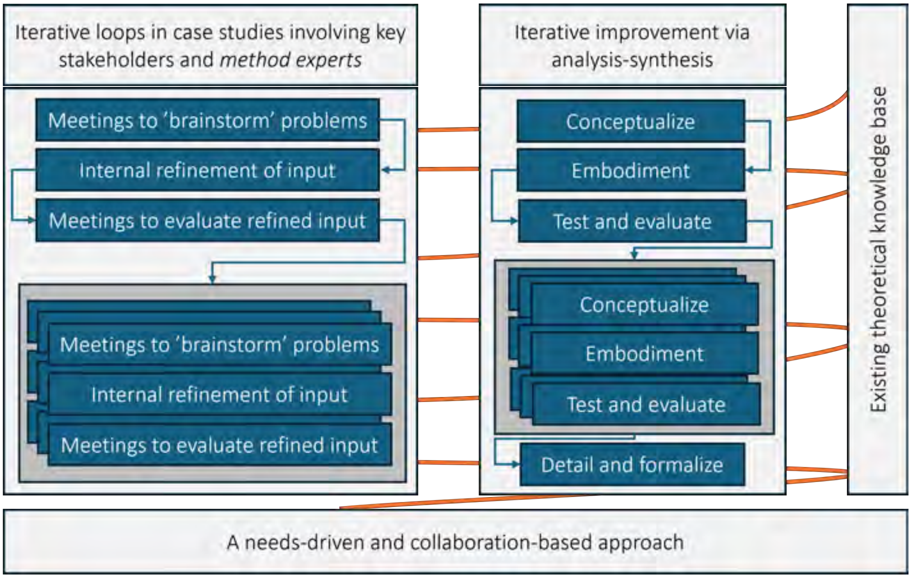


Figure 2.6: The iterative process used in Study 2 to develop and test the adoption approach.

The case studies and data collected in Study 1 were thus "reused" in Study 2 and are therefore not explained again to avoid repetition. However, since Study 2 focused on addressing the problems identified in Study 1, this approach better aligns with *action research* (Lewin, 1946; Ottosson, 2003; Säfsten and Gustavsson, 2020), and is beneficial for three main reasons:

- Design and development practices are, in general, highly complex and unique within any organization, and much unspoken information is available but difficult to uncover without close interaction (Ottosson, 2003), which is necessary to manage the contextual complexity of design method adoption.
- Action research supports researchers in developing a deep understanding of the processes they study and provides opportunities to continuously test

hypotheses (Ottosson, 2003), thereby enabling an abductive development process (Dorst, 2011).

- Action research closely involves stakeholders in the adoption process, which can positively influence human-behavioral aspects towards adoption, or change (Lewin, 1946; Kanter, 1985; Oreg et al., 2011; Burnes, 2015; Deci et al., 2017).

2.3.3 Study 3: Studying factors influencing sustainability information and data management

Study 3 was a descriptive study that expanded on the findings from Study 2. More specifically, investigating factors influencing the sharing and management of sustainability information and data across the value chain. Study 3 was conducted across Projects III and IV and involved several activities to collect qualitative data. The main activities that contributed to Study 3 were two interactive workshops and 13 semi-structured interviews with several industrial actors, predominantly from the automotive value chain. This is briefly visualized in Figure 2.7

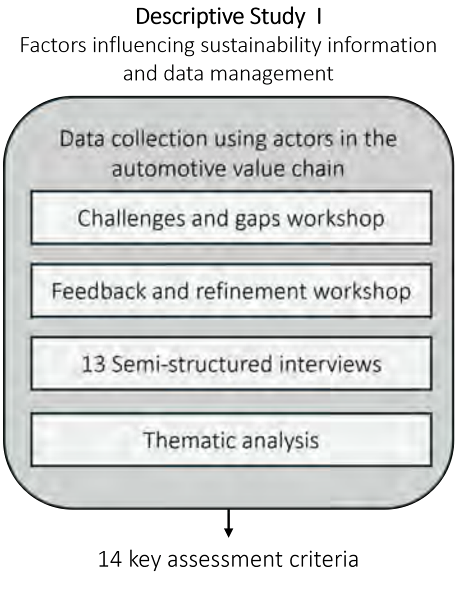


Figure 2.7: Key activities in Study 3.

First, a workshop (4h) was held to identify key challenges and current gaps in the sharing and management of sustainability information and data across the automotive value chain, as a structured brainstorming exercise. Second, a follow-up workshop (2h) was held to refine, streamline, and validate the outcomes of the first workshop. Third, 13 semi-structured interviews were used to identify concrete examples and to generate a more nuanced understanding of the issues stakeholders face in their daily work and how they address them today. The scope of the interviews was not limited to sustainability information and data management; the themes and questions covered are provided in the appendix to Paper D. Table 2.4 presents the participants involved, along with their backgrounds. The participants were purposefully sampled to generate insights concerning sustainability information and data management across the value chain (Eisenhardt, 1989; Flick, 2007; Cash et al., 2022).

Table 2.4: Participants in the activities carried out in Study 3. Participants taking part in more than one activity are provided with an index.

The first workshop (n=9)	*The second workshop (n=6)*	*Semi-structured interviews (n=13)*
Information and data management expert from a PLM solution provider	Sustainability expert from an automotive value chain material supplier	Sustainability and methods expert at an aerospace first-tier supplier
Information and data management expert from a PLM solution provider	Sustainability expert from an automotive value chain material supplier	Sustainability and LCA expert at an aerospace first-tier supplier
Information and data management expert from a PLM solution provider	Circular operations expert at an automotive OEM (2)	Supply chain expert in polymers and sustainability at an automotive OEM (5)
Product data management expert at an automotive OEM (1)	Product data management expert at an automotive OEM (1)	Sustainability and methods expert at an automotive OEM
Circular operations expert at an automotive OEM (2)	Research project coordinator at an automotive OEM (3)	Supply chain expert at an automotive OEM
Circular operations expert at an automotive OEM	Project manager for advanced engineering projects and expert in product platform at an automotive OEM (4)	Sustainability expert at an automotive first-tier supplier
Research project coordinator at an automotive OEM (3)		Expert in product platform at an automotive OEM
Sustainability and LCA expert at an automotive OEM		Circular operations expert at an automotive OEM (6)
Project manager for advanced engineering projects and expert in product platform at an automotive OEM (4)		Sustainability expert at an outdoor power products OEM
		Supply chain and sustainability responsible at an automotive value chain material supplier
		Sustainability and surface materials expert at an automotive OEM (7)
		Product data management expert at an automotive OEM (8)
		Sustainability expert at an automotive value chain material supplier

Following this, using a *thematic analysis* (Säfsten & Gustavsson, 2020), 14 key assessment criteria were derived and generalized from the challenges and gaps identified during the qualitative data collection. A total of five researchers participated in data collection and analysis to enhance rigor and improve the *inter-rater reliability* of the findings (Säfsten and Gustavsson, 2020; Creswell, 2014). In parallel, the literature supported streamlining terminology and strengthening the *external validity* (Säfsten and Gustavsson, 2020; Creswell, 2014).

2.3.4 Study 4: Action Research at an Automotive OEM

Study 4 was conducted within Project V by conducting an *action research* study (Lewin, 1946; Ottosson, 2003; Säfsten and Gustavsson, 2020) at an automotive OEM, referred to as Company X[2]. The overall context concerns Company X's real business scenario, which stems from its ambition to integrate new, more sustainable materials into its products. In turn, they are currently exploring how to achieve this in collaboration with six first-tier material suppliers. Furthermore, to enable this and support early decision-making, Company X needs to request and collect new sustainability information and data on these materials.

Company X, therefore, initiated a research project with these six first-tier material suppliers, referred to as a *sustainable materials data ecosystem*, to explore how access to high-quality, mature sustainability information and data can be improved. The author of this thesis was invited to support this initiative on-site at Company X, i.e., the *action research* study, and started in February 2025 and ended in line with the finalization of this thesis. In turn, this enabled the development and testing of an assessment method that built on the results from Study 3, serving as a Prescriptive Study and a Descriptive Study II in relation to Study 3. Moreover, the adoption approach developed in Study 2 was used to guide and structure the action research study, thereby serving as a Descriptive Study II in relation to Study 2. This is visualized in Figure 2.8.

[2]This is the same automotive OEM that was involved in Studies 1-3.

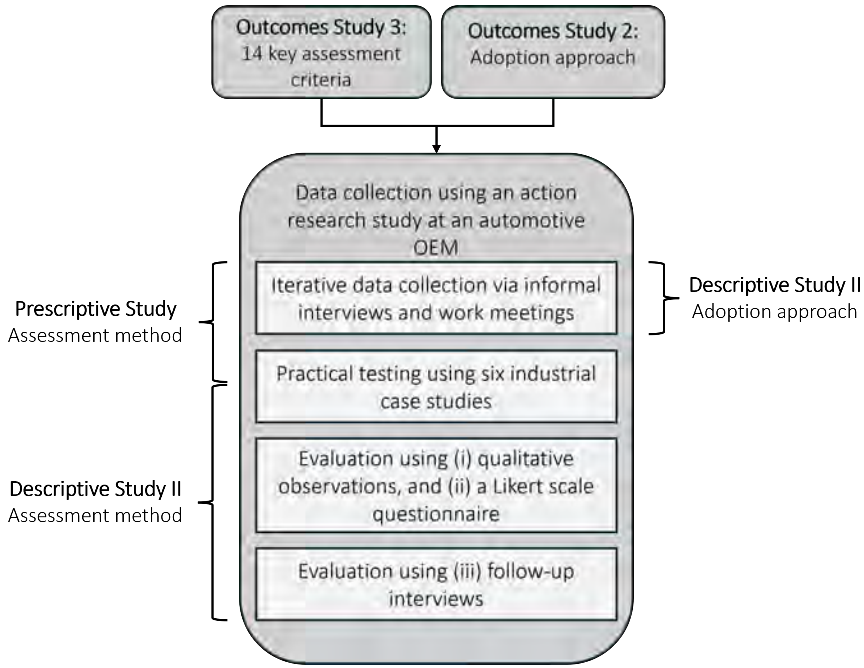


Figure 2.8: Key activities in Study 4 and how they relate to Study 2 and Study 3.

2.3.4.1 Data collection using action research

Action research (Lewin, 1946; Ottosson, 2003; Säfsten and Gustavsson, 2020) was considered a suitable approach, as it aligns with the arguments in Studies 1 and 2, i.e., is useful for obtaining a deep contextual understanding and positively influences human-behavioral aspects towards adoption. Altogether, this ensured that the descriptive findings from Study 3 could be utilized in a relevant way, while in turn, also enabling practical testing of the adoption approach in a more operational environment. Moreover, this also aligns with Ketokivi and Choi (2014)'s view on *theory elaboration*, which focuses on incorporating *contextual idiosyncrasies* in existing theories. Furthermore, several means, or 'tools', were used to support the action research study at Company X:

- Acquiring an internal company email, key badge with access to the site, and access to Teams channels, which significantly increased access to key stakeholders inside the organization and complementary information about their roles and responsibilities.

- Access to internal databases with documentation of, e.g., organizational structure, templates for internal methods and tools, terminology, and development process charts.

- A template that Company X uses for both internal and external communication was used with the intention of making presentation material appear as 'made here'.

- Physically located at the company during meetings and key activities, for two to three days a week, for the initial three months of the study.

From February 2025 to August 2025, more than 30 informal work meetings and interviews were conducted to understand this organizational context. For example, getting acquainted with the company's internal language, daily challenges and priorities, formal roles, existing methods and tools, and design processes. These informal meetings involved different internal stakeholders, including:

- Product designers and component owners to better understand how they work with product development and integrate sustainability, along with the challenges they face concerning sustainability information and data.
- Managers and other 'gatekeepers' who are responsible for internal resources and might have input about what challenges to prioritize.
- Material specialists to better understand what sustainability data is available, but also what data could be relevant for Company X, and how it could improve and support the decision-making process concerning material selection.
- Representatives from the information and data management/PLM function to better understand what internal data structures and rules are important to consider, what other tools exist, and the internal data flows.
- Database governance representatives, as data is scattered across the organization, where several databases are used to store and manage it, and it is important to find synergies and overlaps with the sustainable material data ecosystem
- Representatives from the purchasing function who are negotiating with material suppliers and have ongoing sustainability initiatives related to the sourcing of materials. They also need sustainability information and data to improve and support decision-making regarding material procurement.
- Sustainability experts and 'champions' to better understand what challenges they experience in integrating sustainability into the design process, what priorities they see, and how the sustainability information and data could improve and support the decision-making on material selection.

Several similar meetings were also held with representatives from the material suppliers for the same purpose. Learnings and insights from the action research study were continuously captured and used to iteratively develop an assessment method, serving as a Prescriptive Study in relation to Study 3, and can best be described as an *abductive process* (Säfsten and Gustavsson, 2020; Dorst, 2011). As mentioned, the 14 key assessment criteria from Study 3 served as the core of the assessment method, whereas this study (i.e., Study 4) instead focused on understanding how these can be integrated into an interactive, cross-functional method that simultaneously promotes ownership, shared understanding, aligned expectations, and awareness of key issues to be resolved together (Ritzén and Lindahl, 2001; Schöggl et al., 2024). Altogether, this resulted in a proposed procedural logic and intended use. For example, which roles to involve, the overall steps to take, and the order in which to take them. Moreover, a template was created to provide a step-by-step, practical guide to the assessment and to capture the outcomes. Thus, serving as a Prescriptive Study in relation to Study 3. Furthermore, as mentioned, the adoption approach supported this adaptation and adoption process, thus serving as a Descriptive Study II in relation to Study 2. Some of these results have not been published in any paper and will instead be introduced in Section 6.4 to discuss the validity of the adoption approach.

2.3.4.2 Practical test of the assessment method

The final assessment method was subsequently applied and tested with Company X and the six first-tier suppliers. A multiple-case study design was employed in the action research study (Eisenhardt, 1989; Säfsten and Gustavsson, 2020) to structure testing in as realistic a context as possible, serving as a Descriptive Study II in relation to Study 3. A total of six real industrial cases were carried out, and the case companies are listed in Table 2.5. As mentioned, six cases are generally considered sufficient (e.g., Eisenhardt, 1989).

Table 2.5: The case companies involved in the six case studies in Study 4.

Company	*Type*	*Size*	*Case*
Company X	OEM in the automotive value chain	90,000+ employees	1, 2, 3, 4, 5, and 6
Company B	First-tier steel supplier in the automotive value chain	15,000+ employees	1
Company C	First-tier aluminum supplier in the automotive value chain	3,500+ employees	2
Company D	First-tier polymer supplier in the automotive value chain	1,100+ employees	3
Company E	First-tier polymer supplier in the automotive value chain	300+ employees	4
Company F	First-tier polymer supplier in the automotive value chain	6,900+ employees	5
Company G	First-tier biomaterial supplier in the automotive value chain	2 – 10 employees	6

The six case studies, one per material supplier, were identical in scope and focused on Company X, the focal company in the collaborative ecosystem, which is seeking to incorporate new sustainable materials into its parts and components by engaging with its material suppliers. Moreover, the cases were purposefully sampled and designed (Flick, 2007; Cash et al., 2022) to generate situation-specific knowledge about how the assessment of a collaborative ecosystem's ability to appropriately share and manage sustainability information and data can be guided and facilitated (Eisenhardt, 1989; Ketokivi and Choi, 2014).

Following this, the proposed assessment method was applied in line with its intended use across six carefully selected multidisciplinary teams from the automotive OEM, together with representatives from the first-tier suppliers, who engaged in a facilitated dialogue on the 14 key assessment criteria during a 3-hour workshop. This setup is illustrated in Figure 2.9, in which 24 people from the seven case companies took part. Additionally, six representatives from academia participated to support the dialogue and made *qualitative observations* within these groups (Creswell, 2014). Moreover, the researcher active in the action research study supported the workshop by describing the method, clarifying its intended use and purpose, answering general questions and concerns, tracking time and progress within each team, while also making *qualitative observations* across all six groups.

Before the workshop, an Excel list with 40+ sustainability data points was defined and created to serve as input, i.e., the sustainability information and data to be assessed. This was done using an adapted version of the *Sustainable Product Development Workshop Method* (Schulte & Hallstedt, 2018a), combined with input collected during the action research study on product criteria used internally to assess the sustainability performance of alternative concepts at company X.

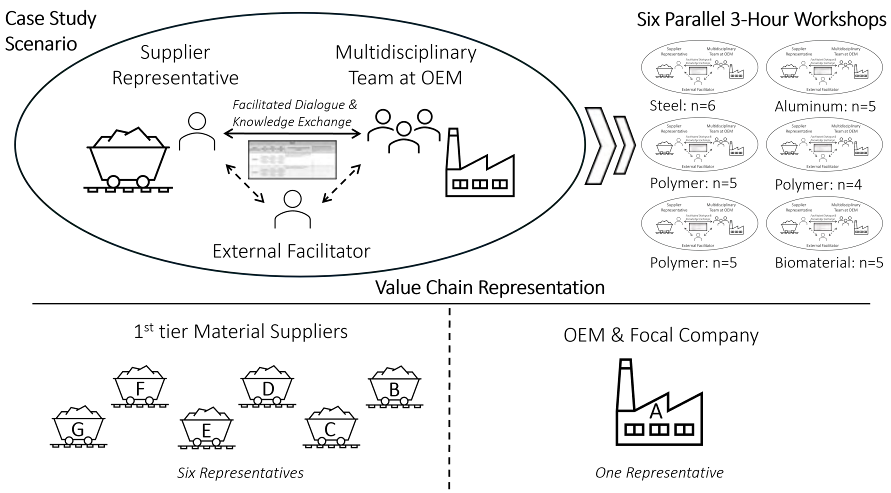


Figure 2.9: Case study design and setup in Study 4.

2.3.4.3 Data collection to evaluate the assessment method

Three different methods were used to triangulate and collect qualitative data used to evaluate the proposed assessment method's effectiveness and applicability (Eisenhardt, 1989; Säfsten and Gustavsson, 2020). **First**, outcomes were captured during the workshop through *qualitative observations* by the academic participants (Creswell, 2014) and through visual recordings using the guiding template. These observations and recordings were later digitized for recordkeeping purposes and later analyzed by the involved researchers. These results were used to evaluate whether and how the assessment method effectively guided and facilitated the assessment of a collaborative ecosystem's ability to share and manage sustainability information and data appropriately.

Second, at the end of the 3-hour workshop, the participants were asked to evaluate the method using a questionnaire (n=22) with Likert-scale responses, to understand how method users perceived it. The questionnaire was inspired by Rossi et al. (2016) and Almefelt (2005), who propose several criteria for evaluating methods. The questionnaire structure and questions used are in the appendix to Paper D.

Third, six follow-up interviews were conducted to evaluate whether and how the assessment method effectively guided and facilitated the assessment of a collaborative ecosystem's ability to share and manage sustainability information and data appropriately. These interviews more specifically focused on following up:

a) What, and if any, key insights and new knowledge were gained among the six teams.

b) If these resulted in any key actions within the sustainable material data ecosystem.

c) The anticipated impact of acting on these outcomes.

In total, seven interviews were conducted: one per team (between October 2025 and November 2025) and one with the project manager from Company X (in February 2026), as this person has a holistic view of (a-b) from a project perspective. The results from these follow-up interviews were synthesized and analyzed by the researcher taking part in the action research study. However, *peer debriefing* (Creswell, 2014; Säfsten and Gustavsson, 2020) was conducted by involving and discussing the findings with peers.

2.4 Ethical considerations

The study objects are, in many cases, individuals, but occasionally also representatives of large organizations that strive to be competitive. The main ethical consideration from a human-individual perspective is that the study subjects are kept confidential and that no personal data is recorded or disclosed. The representations made of the organizations are, in turn, also treated as confidential. Rich data has therefore been simplified and/or generalized to avoid revealing, e.g., individuals, company-specific, or sensitive information. Informed consent has been achieved through standard agreements between partners in the projects.

Chapter 3

Frame of reference

This chapter provides the frame of reference for this research. First, different perspectives on design processes are presented to provide background on how design is typically governed. Second, design theory, or design as a human activity, is elaborated. Third, previous work in sustainable design is presented. Fourth, the design methods used in this research are presented. This includes *Sustainable Product Development* (SPD) design methods, which clarify the lens for sustainable design adopted in this research. These SPD design methods are then argued to benefit from being used in conjunction with a *Systems Engineering Design* (SED) approach, and a set of such design methods has also been used in this research. Fifth, design methods are clarified in general terms, and their role in design is explained. Sixth, previous research on the industrial adoption of design methods is presented, highlighting a research gap. Last, in response to the research gap, perspectives from the management domain are presented.

3.1 Design processes and the early phases of design

In manufacturing companies, design processes are central to structuring, governing, and facilitating design activity, and several generic models of design processes exist in literature (e.g., Ullman, 1992; Pahl et al., 1996; Ulrich and Eppinger, 2016). However, any designer's or design team's design context manifests differently in practice and is difficult to specify, pinpoint, and communicate effectively and efficiently (Maffin, 1998; Ottosson, 2003; Gericke et al., 2020 & 2021). This specific design context or process differs in many ways, including the design activities and their order, the design problem at hand, the involvement of external and internal actors, the available information and data, the design logic, and the terminology. Ullman (1992), nevertheless, argues that the following steps are necessary regardless of what *design problem* is to be solved.

- Establish the need or realize that there is a problem to be solved.
- Plan how to solve the problem.
- Understand the problem by developing requirements and uncovering existing solutions or similar problems.
- Generate alternative solutions.
- Evaluate the alternatives by comparing them to the design requirements and to each other.
- Decide on acceptable solutions.

Pahl et al. (1996) argue that the main phases of design are: (a) Product Planning and clarifying the task; (b) Conceptual design; (c) Embodiment design; and (d) Detailed design. Eder (1998), similarly, divides designing into the four phases of (i) understanding the problem, (ii) conceptualizing, (iii) embodiment, and (iv) detailing. Ulrich and Eppinger (2016) illustrates a generic product development process as visualized in Figure 3.1, which also share characteristics with the proposals above. Ulrich and Eppinger (2016) defines such a process as the "sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product".

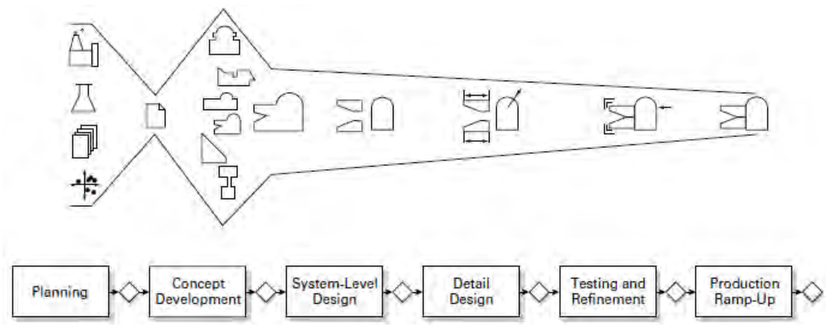


Figure 3.1: Illustration of a product development process (Ulrich & Eppinger, 2016).

Eder (1998) refers to (i) and (ii) as the 'early stages' of designing, claiming that most impact on the final product is made there. In these phases, design freedom is high, but less is known, which increases uncertainty and results in a well-known dilemma referred to as the design process paradox (Ullman, 1992; Bhander et al., 2003; Chebaeva et al., 2021). However, key design decisions about materials, new technologies, product platforms, manufacturing, preliminary requirements, and suppliers are still made in these early phases (Ulrich & Eppinger, 2016). This, in turn, adds constraints that reduce the design space and significantly influence potential solutions. *Front-loading* is a common strategy to counter this dilemma, where the goal is to push knowledge generation as early as possible in the design process (Ullman, 1992; Thomke and Fujimoto, 2000), and is considered critical to developing sustainable solutions

(Bhander et al., 2003; Ramani et al., 2010; Hallstedt et al., 2023b). Ullman (1992) states that:

> "The goal during the design process is to learn as much about the evolving product as early as possible in the design process because during the early phases changes are least expensive".

The intent of this section is to generally position design processes as effective for structuring, governing, and facilitating design activity, while highlighting the importance of the early phases.

3.2 Perspectives on designing as a human activity

This section provides general perspectives on the breadth of designing as a human activity and what characterizes it, and Pahl et al. (1996), for example, claim that:

> "Designing is a creative activity that calls for sound grounding in mathematics, physics, chemistry, mechanics ... and design theory as well as knowledge and experience of the domain of interest".

As mentioned in the introduction, Simon (1969) stated that "everyone designs who devises courses of action aimed at changing existing situations into preferred ones" and that designing "is concerned with how things ought to be, with devising artifacts to attain goals". Gregory (1966) claimed that designing as an activity is present irrespective of whether it relates to the design of an oil refinery or writing Dante's Divine Comedy. Willem (1990) stated:

> "Designing is the expression of an innate human ability, an ability to change the environment presumably for the better."

Asimow (1962), generally, views designing as the cycling between problem formulation, synthesis, and evaluation, which follows Arnold (1956)'s approach to solving *creative problems*. Jones (1992) decomposes design into three modes: diverging, transformation, and converging, which can be understood as distinct modes of acting or thinking in design. These general modes of thinking align with Faste (1994), who frames the cognitive ability to switch between the analytic and creative modes of thinking at will as *ambidextrous thinking*. The Design Council (2005) depicts this effectively using a double diamond, where designers work iteratively between a problem and solution space in a diverging-transforming-converging manner. Together, this highlights the breadth of design, and aspects of design as a cognitive activity have, for example, been documented in the writing of letters and in the formation of names (J. C. Thomas & Carroll, 1979). Designing can thus relate to the design of a light bulb, a business, a production setup, a cogwheel, 'the best passage to work', or solutions in complex military situations (e.g., Banach and Ryan, 2009). The process of designing, as such, is often acknowledged as a cognitive or mental activity inherent to humans in the design domain (Ullman, 1992; Pahl et al., 1996), and has been thoroughly studied from a cognitive perspective as well (e.g., Simon, 1969).

As previously postulated, design, or any design process, can generally be seen as a knowledge-producing process in which various design activities help designers better understand the problem and its potential solutions. Dorst and Cross (2001), for example, refer to this as the co-evolution of problem and solution, which explains the iterative nature of design, where both the problem and solution spaces evolve as we learn more about the problem and its potential solutions. Schön (1992) referred to this as a "reflective conversation with the situation". Ullman (1992) also stated that:

> "Throughout the solution process knowledge about the problem and its potential solutions is gained".

The design process or designing is thus argued to support designers to better acquaint themselves with the problem and its potential solutions, where the overall goal is to identify a good problem-solution fit (Cross, 1992; Dorst and Cross, 2001; Ullman, 1992; Dorst, 2006). In the context of engineering design, Pahl et al. (1996) more concretely state that:

> "Design is an engineering activity that provides the prerequisites for the physical realisation of solution ideas".

In turn, designing is generally beneficial to address design problems, i.e., problems that are not easily understood and tend to be referred to as 'creative', 'ill-structured', 'ill-defined', 'wicked', 'open-ended', and 'unique' problems (Arnold, 1956; Simon, 1969; Rittel and Webber, 1973; Archer, 1979; Buchanan, 1992; Dorst, 2006; Dorst, 2011; Auernhammer and Roth, 2021; Gericke et al., 2022). Such *design problems* do not have one obvious solution, if any at all, and can rather be seen as good or bad rather than true or false (Rittel & Webber, 1973). A *design problem* can, for example, relate to 'how to transport users from A to B', 'how to design a lightweight airplane foil', 'how to design a circular supply chain', or 'how to design a music festival'.

There have, for example, been claims that *design problems* are paradoxical in the sense that: (i) designers do not know the 'real' *design problem*, or at least do not fully understand it before they have engaged in the early phases of design (Archer, 1979; Dorst, 2006); and (ii) the *design problem* can only be fully understood in the light of the solution, or as Cross (1992) states,

> "A design solution is not an arbitrary construct – it usually bears some relationship to the problem as given".

Marples (1961) also highlighted this while also clarifying the necessity of generating alternative solutions to *design problems*.

> "The nature of the problem can only be found by examining it through proposed solutions and it seems likely its examination through one, and only one, proposal gives that a very biased view".

This further nuance *designing*, while also clarifying why the process of finding potential and appropriate solutions (i.e., 'products', 'designs', or 'artifacts') to such *design problems* is not obvious. And, in turn, benefits from adhering to *design theory*, or what is occasionally referred to as *designerly ways of knowing, thinking, and acting* (Cross, 1982; Dorst and Cross, 2001; Dorst, 2011; Cross, 2023a). For example, iterate between the problem and solution space, apply front-loading strategies, and explore several alternative solutions.

The intent of this section is to generally position the breadth of designing as a human activity and its characteristics to underpin and clarify why *design*, as a process and/or human ability, can play a crucial role in a sustainability transition.

3.3 Sustainable design

Brundtland (1987) provides one of the more acknowledged definitions of *sustainable development* as:

> "Meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs".

However, Sala et al. (2015) highlighted the challenge of understanding "what contributes to a sustainable development and what does not". *Design* has, in turn, been identified as an enabler of sustainable development efforts, and the notions of *designing* as a human activity, and *design problems*, as presented in the sections above, underpin and clarify why *design*, as a process and/or human ability, can play a crucial role in developing solutions and contribute to sustainable development (e.g., Klotz et al., 2018; Baldassarre et al., 2020). Baldassarre et al. (2020), for example, broadly define *sustainable design* as "the rational and structured process to create something new for solving sustainability-related problems". However, effectively integrating ecological, social, and economic sustainability considerations into the design process is challenging, and it has been argued that this, in turn, requires appropriate skills, knowledge, and the adoption of several design methods for sustainable design (Faludi et al., 2020; Hallstedt et al., 2023a). Therefore, design researchers in the domain of sustainable design have proposed several means to support manufacturing companies in integrating sustainability into the design process (e.g., Karlsson and Luttropp, 2006; Ahmad et al., 2018; Faludi et al., 2020; Hallstedt et al., 2023a).

This ranges from how to, e.g., implement eco-design in the design process (Ritzén and Beskow, 2001; Johansson, 2002; Blizzard and Klotz, 2012; Pigosso et al., 2013; Bocken et al., 2014; Brones et al., 2021) to separate tools, methods, or strategies to support specific design tasks or design decisions (e.g., Luttropp and Lagerstedt, 2006; Faludi et al., 2020; Carlsson et al., 2021; Hallstedt et al., 2023b; Parolin et al., 2025). For example, the *10 golden rules* (Luttropp & Lagerstedt, 2006) and the *9R framework* (Potting et al., 2017) can guide the design of more environmental and resource-efficient solutions. Bocken et al., 2016 suggests that designers should actively design products to (i) slow resource loops, (ii) close resource loops, and (iii) narrow resource flows. Ulrich and Eppinger (2016) dedicates a chapter to Design for Environment, which focuses on minimizing the environmental impact of products. Ceschin and Gaziulusoy (2016), instead, proposes a framework that synthesizes research in the field they refer to as *Design for Sustainability*, and argue it has progressed from viewing sustainability as a technical, product-centric, and mainly environmental issue to a much larger and more complex challenge that expands over multiple levels within the global socio-technical system.

The intent of this section is to acknowledge that much work has been done across different fronts in the area of *sustainable design*, indicating a substantial body of knowledge is available, including several design methods for sustainable design. The design methods used in this research are described in the section below, while also clarifying the lens adopted for *sustainable design* in this thesis.

3.4 Design methods used in this research

This thesis has used two categories of design methods to study industrial adoption, and the rationale for this choice was described in Section 2.2. These design methods are presented in further detail below.

3.4.1 Sustainable product development

To study the industrial adoption of design methods for sustainable design, this thesis has more specifically used SPD design methods, which are based on more than 15 years of research in close collaboration with the Swedish product development and manufacturing industry (e.g., Byggeth and Hochschorner, 2006; Hallstedt et al., 2023b; Watz and Hallstedt, 2024). The SPD design methods aim to support the integration of socio-ecological sustainability into the early phases of the product innovation process, using a holistic, systemic, and systematic approach to sustainability, e.g., by applying elements within the *Framework for Strategic Sustainable Development* (e.g., Broman and Robèrt, 2017; Broman and Robèrt, 2025). This framework, for example, comprises eight principles that define socio-ecological sustainability. These eight principles are explicitly defined (Broman & Robèrt, 2017): "In a sustainable society, nature is not subject to systematically increasing...

1. Concentrations of substances extracted from the Earth's crust.

2. Concentrations of substances produced by society.

3. Degradation by physical means.

And people are not subject to structural obstacles to

4. Health

5. Influence
6. Competence
7. Impartiality
8. Meaning-making.

The FSSD also provides guidelines for adopting a strategic approach to sustainable development. This, for example, includes the use of a forecasting and backcasting approach: (i) The vision is identified and formulated; (ii) The barriers to realizing the vision are identified and formulated; (iii) The required steps to reach the vision are identified and formulated; (iv) The different steps are prioritized. Although this thesis refrains from providing a distinct and unequivocal definition of *sustainable design*, the elements and facets above clarify what is meant by *sustainable design* in this thesis.

Several SPD design methods have been proposed, which operationalize on FSSD to support practitioners in, e.g., anticipating the sustainability performance of different solutions (Hallstedt et al., 2023b), identifying sustainability-related risks (Schulte et al., 2020), and providing guidance towards more sustainable solutions (Watz & Hallstedt, 2024), and guiding material selection (Hallstedt & Isaksson, 2017). Applying the SPD design methods in this thesis typically involved a 2–3h facilitated workshop with a multidisciplinary team of practitioners, including various designers, experts, and/or specialists within the organization, during which a set of key questions or focused topics was discussed. This information is later consolidated either by design researchers (i.e., *method experts*) or practitioners, and the outcome is typically communicated and used by relevant stakeholders inside and outside the organization. This research has used eight distinct design methods, or approaches, that stem from SPD research to study industrial adoption: (i) Leading Sustainability Criteria Workshop (e.g., Watz and Hallstedt, 2024); (ii) Sustainability Fingerprint (e.g., Hallstedt et al., 2023b); (iii) Group Model Building (e.g., Watz, 2020); (iv) Profile model for management of sustainability integration in engineering design requirements (e.g., Watz and Hallstedt, 2020); (v) Sustainability impact and effects analysis (e.g., Schulte et al., 2020); (vi) Strategic Lifecycle Assessment (e.g., Villamil et al., 2018); (vii) Self-assessment method for sustainability implementation in product innovation (e.g., Schulte and Hallstedt, 2018b; and (viii) Strategic layered double-flow scenario modeling for sustainability risk and portfolio management method (e.g., Villamil and Hallstedt, 2021).

3.4.2 Systems engineering design

This thesis has not focused solely on the industrial adoption of SPD design methods, but also on their use in conjunction with SED methods. The SED design methods used in this thesis are based on more than 20 years of research in close collaboration with the Swedish product development and manufacturing industry (e.g., Isaksson et al., 2000; Isaksson et al., 2013; Borgue et al., 2021). Many developed products today can be seen as parts of larger, complex, and evolving systems, thereby further underpinning the growing complexity of the *design problems* that organizations are expected to solve. In turn, positioning the relevance of *Systems Engineering Design* (Isaksson et al., 2023) approaches as a complement to SPD. The overall intent is that a combined SPD-SED setup can enhance the integration of socio-ecological sustainability perspectives in complex systems. Some recent examples include Martinsson Bonde et al. (2025), who combined a functional architecture modeling approach together with a "relative sustainability fingerprint". Another example is Al Handawi et al. (2021), who integrated remanufacturing considerations in a modeling approach.

Furthermore, the SED design methods generally aim to support the modeling and design of complex systems with multiple dependencies and interactions across different domains and subsystems (e.g., system functions, stakeholders, and/or the engineering disciplines used in the system). Moreover, such dependencies are later evaluated jointly in the early phases of design, which ultimately supports practitioners in assessing the impacts of different design decisions on complex socio-technical systems (Isaksson et al., 2023). Applying the SED design methods in this thesis typically involved collecting data and information from different stakeholders in the organization, which were later incorporated and/or modeled in computer-based tools by either a design researcher or a practitioner (i.e., a *method expert*). The outcome is later communicated and utilized across organizations to enable more information-based design decisions. This research has used three distinct design methods, or approaches, that stem from SED research to study industrial adoption: (i) Three sub-methods that are part of the Value-driven design methodology (e.g, Isaksson et al., 2013); (ii) Digital Design Experiments (e.g., Martinsson Bonde et al., 2022a); (iii) Design for test and qualification through activity-based modeling (e.g., Borgue et al., 2021). However, it should be reiterated that this research does not advance the underlying logic and elements of the design methods; rather, it aims to contribute knowledge that clarifies why the industrial adoption of SED and SPD design methods can be challenging yet also facilitated and improved.

3.5 Clarifying design methods

Design researchers have, over the years, proposed a plethora of design methods, commonly referred to as 'formalized', 'theory-based', or 'industry best practices' (Eder, 2009), and the overarching goal of any such design method is to support the development of better products (Cross, 2023b; Blessing and Chakrabarti, 2009). Moreover, there have been various claims about what a design method actually is. Cross (2023b), for example, broadly claimed that:

> "In a sense, any identifiable way of working, within the context of designing, can be considered to be a design method".

Jones (1992) argued that design methods are:

> "Attempts to make public the hitherto private thinking of designers; to externalize the design process"

And Eder (1998) also describes them as:

> "Prescriptive knowledge as advice about designing ('know-how')".

Wallace (2011) defines a design method as:

> "A prescriptive plan of action by which a class of design tasks are tackled."

Moreover, Daalhuizen and Cash (2021) stated that a design method is an encapsulation of procedural knowledge, key to designing, and the design process. In essence, design methods are recognized as artifacts that guide the design activity. Similarly, Gericke et al. (2022) argue that design methods, indeed, are artifacts in their own sense:

> "A description of a method is an artefact in its own right. It is an embodiment of engineering knowledge, available for engineers to draw on and employ more or less exactly."

Following this, Gericke et al. (2022) also provides the following definition of a design method:[1]

> "A specification of how a specified result is to be achieved. This may include specifications of how information is to be shown, what information is to be used as input to the method, what tools are to be used, what actions are to be performed and how, and how a task should be decomposed and how actions should be sequenced."

Each specific design method serves a specific purpose related to the design activity, but they generally improve communication, reduce development time and costs, and rationalize the design process (Ulrich & Eppinger, 2016). Design method(s), as an umbrella term, can thus be considered broad, since different methods address different aspects of design, and apply to different situations as well as product or artifact types. Nevertheless, it is possible to argue that the role of any design method generally is to prescriptively guide designers in generating a set of specific knowledge related to the *design problem* 'at hand'. Gericke et al. (2022), similarly, stated that:

> "A method is a kind of promise: follow the outlined steps and you should be able to get a certain kind of result. [...] A design method is supposed to achieve something: it is supposed to generate new information about the design. Beyond that, it is hard to generalise."

This information, or knowledge, in turn, preferably supports meeting the overall goal of identifying a good problem-solution fit (Cross, 1992; Ullman, 1992;

[1] Gericke et al. (2022) separates the term design method from a tool, where 'tools' can be seen as a means to facilitate the adoption of a design method. This thesis acknowledges this, but, for simplicity, does not try to distinguish between the two.

Dorst and Cross, 2001; Dorst, 2006), or proposing a 'better' product (Blessing and Chakrabarti, 2009; Cross, 2023b). This logic is summarized and illustrated in Figure 3.2, which uses the design process paradox (Ullman, 1992) to show how design methods (the red rhombs) support the generation of different kinds of knowledge throughout the design process.

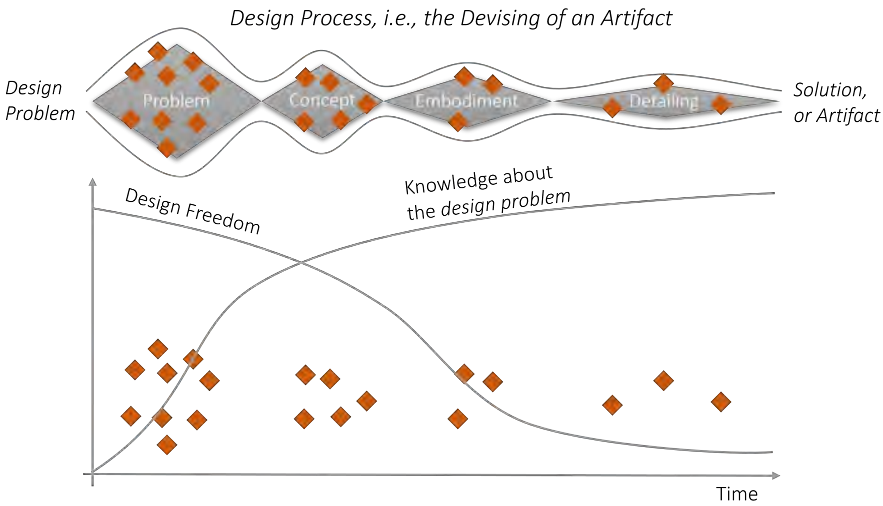


Figure 3.2: A generic design process influenced by Eder (1998) mapped against the design process paradox (Ullman, 1992). Design methods are illustrated as red rhombs that support various design activities along the design process and generate knowledge about the *design problem*.

3.6 Industrial adoption of design methods and the research gap

However, despite the benefits of design methods, their industrial adoption remains limited (O'Hare et al., 2010; Faludi et al., 2020; Watz and Hallstedt, 2022). Moreover, many reasons why adoption is limited have been raised for any design method (e.g., Eder, 1998; Araujo et al., 1996; Booker, 2012; López-Mesa and Bylund, 2011), but also specifically for sustainable design (e.g., Lindahl, 2006; Boks, 2006; Ritzén and Lindahl, 2001; Vicente and Camocho, 2024). To give an idea, Table 3.1 lists a set of factors raised for the adoption of any design method, and Table 3.2 instead lists a set of factors raised for the adoption of design methods focused on sustainability. These lists include identified factors influencing adoption, both barriers (B) and enablers (E), marked with 'X' in the tables to indicate the factor. An unmarked factor may be either a barrier or an enabler.

Table 3.1: List of factors, both barriers (B) and enablers (E), influencing the adoption of any design method. The list provides a sample illustrating typical aspects discussed in the literature. 'X' indicates if it was suggested as a barrier or an enabler, and no indication means it is neutral.

Eder (1998)	**B**	**E**
Must be adapted to the context	X	
Success at first usage	X	
Only required when designers face new problems		
Industry tries to implement a complex method all at once and fails, which leads to rejection	X	
Require a good understanding of the theory behind the method	X	
Araujo et al. (1996)		
Companies are unaware of the existence	X	
Companies are unaware of the quality of methods	X	
Contextual differences between companies and methods use	X	
Require experienced or trained staff to use methods	X	
Booker (2012)		
Availability of data		X
Integration with existing tools		X
López-Mesa and Bylund (2011)		
Academia studies design processes in isolation from engineers	X	
Methods are not studied sufficiently before being used or tested by practitioners	X	
The company lacks systematic processes in place	X	
Methods are inappropriate	X	
Inappropriate support for method uses	X	
Inappropriate use of the method	X	
Inappropriate implementation of the method	X	
Benefits are not realized immediately	X	
Not enough time to learn the method	X	
Not enough time to use the method	X	
Incorrect use leads to bad results	X	
Methods are adopted based on popularity		
Not user-friendly instructions	X	
Engineers unaware of methods	X	
Lack of guidance on how to use methods	X	
People do not want to change how they work	X	
Lack of computer support	X	
Methods reduce freedom and are boring	X	
Engineers are not trained to use methods	X	
The value is only understood once you use it	X	

Table 3.2: List of factors, both barriers (B) and enablers (E), influencing the adoption of design methods focused on sustainability. The list provides a sample illustrating typical aspects discussed in the literature. 'X' indicates if it was suggested as a barrier or an enabler, and no indication means it is neutral.

Vicente and Camocho (2024)	**B**	**E**
Time to use the tool	X	
Cost of using the tool	X	
The need for data	X	
Effort versus results		
Seamless integration into the current design practices		
Can be used autonomously without experts		X
Align with the needs of designers		X
Lindahl (2006)		
To what extent it is experienced as beneficial		
The primary purpose of the method		
Level of complexity		
The method must provide benefits		
There is a need for training	X	
Unnecessarily complex	X	
Risk of removing good practices	X	
Easy to understand and experience the benefits		X
Easy to understand how it is to be used		X
Adjustable to different contexts		X
Low setup time		X
Not require cooperation		X
Not too high requirements for data		X
Visualization of the results		X
IT Based		X
Give direction, not result		X
The customer requires the utilization of the method		X
Boks (2006)		
The gap between eco-design proponents and those who have to execute it	X	
Lack of cooperation between departments	X	
Tools available in the company are too complex	X	
Lack of management commitment and support	X	
Ritzén and Lindahl (2001)		
Use of qualitative data		X
Easy to understand, learn, and use		X
Facilitate cross-functional collaboration		X

Furthermore, as mentioned in the introduction, several research efforts have sought to address these issues where different proposals have been made, ranging from using qualitative data, educating personnel, and promoting the use of champions, to selecting and adapting design methods (e.g., Eder, 1998; Ritzén and Lindahl, 2001; Johansson, 2002; Lindemann, 2002; Ernzer and Birkhofer, 2002; O'Hare et al., 2010), and many of these are still raised as success factors (e.g., Faludi et al., 2020; Gericke et al., 2020; Lavrsen et al., 2022; Hallstedt et al., 2023b; Vicente and Camocho, 2024; Parolin et al., 2024). At the same time, adhering to method criteria such as 'easier to use', 'less time-consuming', and alignment with *status quo* must be treated with caution, considering the radical changes required to align with sustainable production and consumption (e.g., Bengtsson et al., 2018; Ceschin and Gaziulusoy, 2019). This dilemma was raised and figuratively illustrated in Figure 1.2. Furthermore, the issue of how to appropriately adapt design methods has been raised in prior literature, as it depends on multiple factors (Ritzén and Lindahl, 2001; O'Hare et al., 2010; Gericke et al., 2021; Brones et al., 2021; Stacey et al., 2025).

However, although many studies have addressed the industrial adoption of design methods from different perspectives, the issue nevertheless remains a contemporary concern that continues to receive attention (e.g., Faludi et al., 2020; Brones et al., 2021; Vilochani et al., 2024; Vicente and Camocho, 2024; Stacey et al., 2025), and while there are several enablers that have been proposed in the 'design domain', it is evident that the 'managerial' side of industrial adoption, or *change* requires more attention (e.g., Boks, 2006; Geis et al., 2008; López-Mesa and Bylund, 2011; Booker, 2012; Jagtap et al., 2014; Pieroni et al., 2019; Brones et al., 2021.

Altogether, the challenge or problem of industrial adoption of design methods is summarized into five key points:

- Several of the factors that were identified roughly 20 years ago also appear in recent literature, where the overall issue of industrial adoption persists, which indicates that there is still a need to study this further.
- A key recurring and summarizing factor, or argument, is that new design methods proposed for design teams often misalign with how design is practiced in industry and fail to meet important needs. In turn, highlighting the need for finding practical means of addressing this.
- A key recurring and summarizing factor, or argument, is that the new design methods typically require information and data that are unavailable. In turn, highlighting the need for finding practical means of addressing this.
- The lists highlight the complexity and multifaceted nature of industrial adoption but provide limited insights into the managerial perspective. Thus, some of the identified barriers can benefit from greater grounding in and consideration of human behavioral perspectives.
- The four points raised above are arguably applicable to the industrial adoption of any design method. In turn, addressing these issues can be useful to design researchers outside the specific field of sustainable design.

In turn, this provides a solid foundation for justifying this research, which involves studying industrial adoption from process and methodological, organizational, and human-behavioral perspectives. To reiterate, the research problem is stated as follows:

- The industrial adoption of design methods has been thoroughly studied in the design domain, where several barriers and enablers have been proposed. However, the industrial adoption remains a contemporary problem that can be better understood and is in need of practical guidance.

At the same time, there is an underutilized body of knowledge in the management domain that can be used to better understand why this issue persists and to strengthen contributions, thereby advancing research in this topic. In turn, concepts and theories from the management domain are expected to be used in this thesis to strengthen the grounding of the contributions. A set of relevant perspectives is, therefore, presented in the following subsection.

3.7 Managerial perspectives on change

First, it is important to acknowledge that there is research in the 'design domain' that has sought to better integrate managerial perspectives of *change* (e.g., Brones et al., 2021; Faludi et al., 2020; Brones et al., 2017; Boucher et al., 2018; Gould, 2018; Boks, 2006; Johansson, 2002; Ritzén and Beskow, 2001). At the same time, there has been considerable research on the social phenomena of change over the past 75+ years that can help clarify why there are many barriers to the industrial adoption of design methods and how to overcome them. Some of the early and influential works include Lewin (1946 & 1947), along with Coch and French (1948)[2], which are often heralded for laying the foundation of the organization development movement and for having positively impacted organizational change through *action research* (Burnes, 2015). Moreover, there is generally a consensus that change is challenging, and Ford and Ford (2010) portray and summarize why change proposals require attention:

> "People at all levels in most organizations often have more things to do than they have time in which to do them. Most do not respond well to the idea of changing what they are doing while simultaneously being held accountable for continuing to produce their assigned results and keep the machinery of communications running smoothly. Introducing a proposal for change into a group with an already full schedule can be difficult at best and impossible at worst. There will be some reaction, and it is likely to sound negative, in part because people don't always choose – or know how – to communicate productively".

Burnes (2015) highlights that there are typically two different views regarding 'resistance to change' in 'change management literature': (i) Resistance to change is considered rooted in individuals, meaning that humans are naturally inclined to resist change; (ii) Resistance to change is rather a result of the organizational context of change and is not necessarily naturally rooted in individuals, and resistance can thus be facilitated. However, Burnes (2015) argues that it is more sensible to acknowledge and combine the two views, since a large body of literature supports both:

> "The individual and systemic views of resistance need not be seen as irreconcilable per se. If one takes the view that organizations are

[2]Coch and French work builds on Lewin's work as part of the Harwood study.

social systems, it is not contradictory to see resistance as arising from the interplay between the characteristics of the individual and the characteristics of the organization."

There are several human-behavioral theories that provide a better understanding of why individuals behave as they do, thereby supporting the claims that (some) individuals are more inclined to resist change (Oreg, 2003; Oreg et al., 2008; Oreg and Sverdlik, 2011). A recurring theme is the influence of *cognitive biases* and cognitive limitations on our decision-making and actions (Simon, 1969; Tversky and Kahneman, 1974). *Cognitive biases* are defined in many ways, and different biases exist, but they broadly refer to how humans (even experienced researchers) sometimes process and interpret information inaccurately (e.g., Tversky and Kahneman, 1974; Korteling et al., 2018; Da Silva et al., 2023). This can, in turn, lead to errors in judgment, causing actions and decision-making to deviate from rationality, with both positive and negative outcomes (Simon, 1969; Tversky and Kahneman, 1974; Klotz et al., 2018).[3] Several cognitive biases have historically been observed, and some are specific to change, which highlights why change is generally challenging. To give an idea, a set of such cognitive biases is presented in Table 3.3.

Table 3.3: Cognitive biases associated with resistance to change.

Cognitive bias	*Brief description and source*
Cognitive dissonance	Some individuals tend to dismiss facts that misalign with their current views or to be selective in their information processing to reduce discomfort (Festinger, 1957).
Endowment effect	Some individuals tend to value or prefer objects they already possess more than those they do not (Thaler, 1980).
Familiarity bias	Some individuals tend to prefer familiar items over unfamiliar ones (Park & Lessing, 1981).
Loss aversion	Some individuals tend to prefer, or rate, not losing something more than the potential to acquire something new (Kahneman & Tversky, 1979; 1984).
Status quo bias	Some individuals tend to prefer the current situation, i.e., doing nothing, or maintaining one's current or previous decision (Samuelson & Zeckhauser, 1988).
Sunk cost fallacy	Some individuals tend to continue a chosen course of action or decision despite negative outcomes, rather than changing course or altering their initial decision to achieve positive outcomes (Thaler, 1980; Arkes & Blumer, 1985).

In essence, such cognitive biases empower individuals to maintain the status quo despite the benefits of change. In turn, this provides an additional explanation for why design methods are typically perceived as requiring too much time and effort, and it is typically acknowledged that there must be a clear perceived value (Oreg et al., 2011), or 'felt need' (Burnes, 2004), to justify even considering change, and that active facilitation is needed to

[3]The concept of cognitive biases will solely be used on a surface level to nuance barriers associated with industrial adoption, and not from an underlying psychological or cognitive perspective.

overcome initial resistance and achieve social acceptance for any type of change.

In parallel, the power of stakeholder involvement, and its benefits, to facilitate change and reduce resistance have been highlighted by several change management researchers (e.g., Kanter, 1985; Kotter, 1995; Oreg et al., 2011; Burnes, 2015), since first promoted by both Lewin (1946) and Coch and French (1948) via *action research*. Involving people in the process can, for example, increase awareness, create a sense of urgency, and establish ownership, all of which are key to social acceptance (Coch and French, 1948; Kotter, 1995; Oreg et al., 2011; Burnes, 2015). Coch and French (1948), roughly 75 years ago, stated that:

> "It is possible for management to modify greatly or to remove completely group resistance to changes in methods of work and the ensuing piece rates. This change can be accomplished by the use of group meetings in which management effectively communicates the need for change and stimulates group participation in planning the changes."

Moreover, Burnes (2004), more recently, in a re-appraisal of the work by Lewin, stated:

> "Action Research stresses that for change to be effective, it must take place at the group level, and must be a participative and collaborative process which involves all of those concerned [...] He [i.e., Lewin] believed that only by gaining the commitment of all those concerned, through their full involvement in the change process, would change be successful. [...] Consequently, rather than arguing that Lewin saw behavioural change as a top-down process, it would be more accurate to say that Lewin recognized that it [i.e., change] could be initiated from the top, bottom or middle but that it could not be successful without the active, willing and equal participation of all."

And Oreg et al. (2011), in a large literature review on change studies, saw that:

> "As a rule, change recipients who experienced high levels of participation tended to report higher readiness and acceptance of change, appraised change as less stressful and exhibited overall support for the change."

Last, there has been substantial research on work design and motivational theory, in which involvement is similarly highlighted as a crucial element for motivating and fostering social acceptance, thereby reducing resistance 'by design'. Moreover, influential research in this domain includes Herzberg (1966)'s two-factor theory of satisfaction and motivation. Hackman and Oldham (1976) built on this work and outlined which job design factors positively influence internal motivation and acceptance, highlighting *work autonomy* as critical. They define *autonomy* as.

> "The degree to which the job provides substantial freedom, independence, and discretion to the individual in scheduling the work and in determining the procedures to be used in carrying it out".

Thereby emphasizing the necessity of involving employees in the work design itself. Work design and motivational theory have progressed since, but in essence, the same core components are highlighted, i.e., *autonomy*, competence, and relatedness, and are considered basic psychosocial needs at a workplace (Deci et al., 2017).

Altogether, the main insights from research in the management domain are summarized into three key points:

- **Change** is generally seen as challenging, and **perceiving its value is crucial**, which in turn highlights that the social side of change needs to be actively considered in the context of industrial adoption of new design methods.
- **Cognitive biases** associated with change serve as a key concept and plausible explanation for why many barriers to the industrial adoption of new design methods arise, as adoption itself requires some degree of change.
- **Stakeholder involvement** is highlighted as a crucial enabler for overcoming resistance to change in both 'old renowned' and contemporary literature. This argument have also been raised in two separate research fora, (i) in *change management* embodied as *action research*, and (ii) in *work design and motivational theory* embodied as *work autonomy.*[4]

It is worth reiterating that this research aims to incorporate managerial perspectives to an extent where established theories are used to better understand and explain industrial adoption of design methods. However, this thesis does not aim to contribute new knowledge to the field of change management.[5]

[4]Many of the studies on change management, work design, motivational theory, and change have focused on 'blue-collar workers', but it seems reasonable to assume that this applies to designers and design teams as well.

[5]This is also why the author tends to refer to 'old' source literature, rather than state of the art in the change management domain.

Chapter 4

Summary of the appended papers and key research findings

The main research findings for each of the appended papers are presented in this chapter. For each section, an introduction to the appended paper is presented, followed by the key findings that contribute to the thesis, structured according to the formulated research questions. Table 2.1 is presented again for readability.

Table 4.1: Paper A-E's contribution to the RQs. Upper case X = significantly contributing to RQ. Lower case x = partly contributing to RQ. O/o = contributing to RQ but in the context of additive manufacturing.

Papers / *Research questions*	Paper A	Paper B	Paper C	Paper D	Paper E
RQ1: What barriers influence the industrial adoption of new design methods for sustainable design?	X	X	x	X	O
RQ2: In what ways can new design methods support manufacturing companies in their sustainability transition?	X	x		x	
RQ3: How can the industrial adoption of new design methods for sustainable design be facilitated?	x	x	X	X	o

4.1 Paper A: Barriers and Enablers for the Adoption of Sustainable Design Practices Using New Design Methods – Accelerating the Sustainability Transformation in the Manufacturing Industry

Paper A reports on the main results of Study 1 and explores factors influencing the industrial adoption of design methods. This is done by analyzing the qualitative data collected across the six case studies from Project I using *Glaserian Grounded Theory*, as described in Section 2.3.1. Paper A aimed to provide answers to the following research question:

- What influences the adoption of sustainable design practices using new and improved design methods?

There are four key findings from Paper A relevant to this thesis, which are presented in more detail below: (i) A descriptive framework that captures 53 interdisciplinary factors influencing the adoption of sustainable design using new design methods; (ii) Three key enablers; (iii) A conceptual model introducing two new theoretical concepts; (iv) Nine systemic barriers & eight propositions.

4.1.1 A descriptive framework with 53 influencing factors

A descriptive framework that captures 53 interdisciplinary factors influencing the adoption of design methods was developed in Paper A using *Glaserian Grounded Theory* analysis. The descriptive framework is extensive and, therefore, not presented in detail here. Instead, a detailed analysis and explanation of all 53 factors is presented in a structured manner in Paper A.

The factors captured by the descriptive framework in Paper A highlight several barriers to industrial adoption, and provide answers to RQ1. Moreover, the descriptive framework also highlights several enablers to the industrial adoption, and partly provides answers to RQ3.

4.1.2 The enabling effects of design methods

Three key enablers captured in the descriptive framework are worth highlighting, as they clarify how design methods can support manufacturing companies in a sustainability transition. They are described in detail in Paper A, but briefly introduced below.

Factor 51 - design methods transfer understanding of 'how and what' sustainability-relevant information and data to capture to practitioners: Design methods were observed to support designers in creating a common language and representation of sustainability information and data. One designer, for example, stated that the design methods:

> "Provide a common language and shared understanding of sustainability" and "terminology around sustainability."

Furthermore, this clarified what information and data are necessary to retrieve and store from both internal functions and external stakeholders, such as suppliers. One designer, for example, stated that:

> "The method resulted in a way to express component requirements to suppliers."

Another designer stated that:

> "Earlier, procurement did not have the right knowledge about sustainability to be able to make decisions (related to suppliers)."

Factor 52 – design methods transfer 'design know-what' to practitioners: Design methods were observed to increase their awareness and understanding of what *sustainable design* represents. One designer, for example, stated that the main purpose of the design methods is to *"ask the right questions"*. Furthermore, designers held their own assumptions about what *sustainable design* is, and the design methods challenged these presumptions. One designer, for example, stated that:

> "I have learned so much more. I thought I already knew a lot."

Another designer stated that:

> "It supports creating increased awareness."

It was also stated that it supported:

> "shedding light on sustainability."

Factor 53 – design methods transfer 'design know-how' to practitioners: Design methods were observed to increase their awareness and understanding of how to practice *sustainable design*. Furthermore, the design methods prescribed a structured approach to the questions to be answered and to the actions and inputs needed to achieve specific outcomes. One designer, for example, stated that the design methods provide a

> "A structured way of how we can achieve the sustainability goals – where to start and then which actions to take."

Another designer stated that it

> "Provides a structured way of integrating sustainability."

The three enablers captured by the descriptive framework in Paper A highlight how design methods can support manufacturing companies in a sustainability transition, which provides answers to RQ2.

4.1.3 A conceptual model framing design methods as designs

A conceptual model framing *design methods as designs* is also proposed in Paper A, based on empirical findings. First, from a designer's point of view, design methods support in solving their 'problems'. These 'problems' are situational challenges or explicit, unmet needs that arise in the design process when current design practices or methods are considered insufficient. Furthermore, these observed 'problems' are divided into three types or layers: (i) *The Situational design problem*; (ii) *Situational sub-problems*; and (iii) *Contextual problems.*

Type one (**situational design problem**) relates to the core of such 'problems' and is typically how problems in the empirical study were and would be formulated by a designer. *Situational design problems* typically relate to the need, or current challenge, of generating different sets of knowledge considered relevant to the design problem.

Type two (**situational sub-problems**) were, and would, typically not be stated explicitly by designers but are instead sub-problems that have been identified as necessary to solve by, e.g., the *method developer* during the development of the design method. *Situational sub-problems* can, for example, relate to 'how to structure and represent information in a condensed format such that it can be communicated internally to make the design method user-friendly', or 'how to systematically divide sustainability criteria according to lifecycle phases', which might result in a sub-step in the design method.

Type three (**contextual problems**) is important to distinguish from types one and two since these refer to 'problems' that either differ between, e.g., organizations, or products, and are thus contextual. Examples of *contextual problems* included:

- Requests to adapt design methods to company language, or, as some designers referred to it, to make them "companyfied".
- The explicit need to efficiently link the design methods, or rather their accompanying computer tools, to the organization's internal information and data management system.

Contextual problems were, in essence, related to explicit requests to simplify, adjust, and/or modify design methods to better align with their organizational context (e.g., products, internal processes, and 'resources').

Second, as mentioned, design methods were observed to transfer both *'design know-what'* and *'design know-how'* to designers. Together, these two factors highlighted that design methods comprise two halves, or a 'dualism', referred to as the *dualism of design methods* in Paper A. This dual nature was used to frame *design methods as designs*, i.e., solutions to a problem. In turn, this highlights that design methods are value-laden artifacts, or *designs*, serving as means to an end (a 'solution'), where the end (a 'problem') itself is value-laden. That is, this conceptual model highlights the normative value of adopting design methods and how, e.g., assumptions and opinions about sustainable design can influence social acceptance, with implications for industrial adoption.

The conceptual model proposed in Paper A supports nuancing the role of design methods in a sustainability transition, where they are shown to transfer awareness and understanding of sustainable design. Moreover, the conceptual model can be used to better understand the identified barriers, thereby facilitating industrial adoption. Altogether, these findings provide answers to RQ2 and partly RQ3.

4.1.4 Nine systemic barriers and eight propositions

The descriptive framework is also compared and discussed with interdisciplinary literature in Paper A to refine, strengthen, and generalize the empirical findings. The aim was to make the identified barriers and enablers easier to treat in isolation. The full extent of this procedure is provided in Paper A and resulted in nine *systemic barriers* and seven propositions, which are presented in Table 4.2 and Table 4.3. Moreover, the two tables capture and consider the three perspectives to varying extents, as indicated by an “x”. Table 4.2 focuses on findings that were more generalizable for the industrial adoption of any design method. Table 4.3 instead focuses on findings that were specific to sustainable design.

The *systemic barriers* and the eight propositions raised in Paper A summarize key barriers and enablers to the industrial adoption that can be treated in isolation, and provide answers to RQ1, RQ2, and partly RQ3.

Table 4.2: *Systemic barriers* and *propositions* that are more generalizable to any design method. Process and methodological perspective is denoted as P&M, Organizational as O, and Human-behavioral as H-B.

	Systemic Barrier (SB)/Proposition (P)	*P&M*	*O*	*H-B*
SB1a	The *situational design problem paradox* limits a design method's transferability and applicability to practitioners.	x		
SB1b	The *situational design problem paradox* requires a design method to be modified and contextually adapted to be applicable and accepted by practitioners, which is a time-consuming activity requiring method experts.	x	x	
P1a	*Method experts* and/or *developers* and practitioners need to understand the barriers towards adoption in regards to the *situational design problem*, *situational sub-problems*, and *contextual problems*, such that resources are allocated effectively.	x	x	
SB1c	The *Design know-what* must be transferred before the need for the *Design know-how* is perceived, but the *Design know-what* is seldom adopted before adopting the *Design know-how* which introduces the *dualism of design methods paradox*.	x		x
P1b	The *Design know-what* needs to be fully understood or tested before deeming the design method to be of no relevance to the practitioner and their *design problem*. Adopting new and improved design methods can transfer what *situational design problems* and what set of knowledge are relevant to their *design problem*.	x	x	x
SB1d	Adopting new and improved design methods induces process and methodological change which is a well-studied social phenomenon and acts as a natural barrier to adoption.	x	x	x
SB1e	The nature of adopting prescriptive design methods points to reduced autonomy which is a key element in work design and more specifically the *Self-Determination Theory*.	x		x
P1c	Design method adoption should be carried out in a cyclic or iterative nature. First-cycle adoption is an initial trial of the *Design know-how* increasing awareness and understanding via the *Design know-what* i.e., what change is needed. Second-cycle adoption focuses on fully adopting *the Design know-what*, either via the *Design know-how* or by modifying and adapting it to better suit the *situational design problem* and its context.	x	x	x

Table 4.3: *Systemic barriers* and *propositions* specific for the process and methodological context of *sustainable design*. Process and methodological perspective is denoted as P&M, Organizational as O, and Human-behavioral as H-B.

	Systemic Barrier (SB)/Proposition (P)	*P&M*	*O*	*H-B*
SB2a	Organizations' current design practices align with the *paradigm of product design* and result in a systemic process and methodological incompatibility with *sustainable design practices*.	x	x	
P2a	There is a need for a systemic shift away from the *paradigm of product design* towards the *paradigm of sustainable design* to enable the adoption of *sustainable design practices*.	x	x	
SB2b	There is a pragmatic mindset in the *paradigm of product design* where the attitude and social acceptance towards process and methodological conflicts, i.e., the need for change, limits the ability to appropriately adopt *sustainable design practices*.	x		x
P2b	The mindset in the *paradigm of sustainable design* requires a change of attitude and increased social acceptance towards process and methodological conflicts, i.e., the need for change, and is seen as an opportunity to improve and co-evolve towards *sustainable design practices*.		x	x
SB2c	The presence of *cognitive biases* influences the ability to fully embrace and adopt *sustainable design practices* using new and improved design methods which in turn leads to a state of *pseudo-sustainability*.	x		x
P2c	The *cognitive biases* of practitioners can be challenged by practicing *Sustainable design thinking* on all levels of an organization.	x	x	x
SB2d	Product development and manufacturing organizations' current information and data management capabilities are not sufficient to adopt *sustainable design practices*.	x	x	
P2d	Adopting new and improved design methods can support product development and manufacturing organizations to improve their information and data management capabilities.	x	x	

4.2 Paper B: Derive and Integrate Sustainability Criteria in Design Space Exploration of Additive Manufactured Components

Paper B reports on a specific set of case study results from Study 1 and Study 2. More specifically, the sustainable design of a turbine rear structure using laser powder bed fusion, which is referred to as case study A1 in Section 2.3.1. Paper B aimed to provide answers to the following research question:

- How can a systemic view of sustainability be integrated and assessed in early phase design space explorations of additive manufactured components?

To address this question, one SED design method and one SPD design method were adapted and integrated within case study A1. There are three main findings from Paper B relevant to this thesis, which are described in more detail below: (i) An early version of the adoption approach was used to adapt the design methods to the case study context and integrating two separate design methods; (ii) It was shown possible to integrate and compare several sustainability criteria during early design-space explorations of additive manufacturing components by combining two design methods; (iii) A set of challenges in integrating a systemic sustainability perspective into early-phase design space exploration was identified.

4.2.1 Facilitating the adaptation and adoption using the adoption approach

An early version of the adoption approach was used to identify which design methods are needed, where they can be used, and how they can be adapted, integrated, and adopted. Two examples of how it supported this are presented below:

- The adoption approach served as a means for communication between the two design researchers responsible for the two design methods and the stakeholders involved. In turn, this made the design method explicit and the process to identify which design methods are needed more straightforward.
- Mapping the design process also supported understanding of where and how the two design methods could be integrated, as well as the technical actions required to integrate the *leading sustainability criteria*. For example, clarifying the data or input was required to appropriately integrate the criteria into the computerized SED tool.

These examples highlight how the approach supported the integration and adoption of two design methods, and partly provide answers to RQ3.

4.2.2 Integrating sustainability criteria in early design space exploration

The first design method used was the *Leading sustainability criteria workshop* (LEASA), an SPD design method. It was used to identify and formulate *Leading Sustainability Criteria* (Watz & Hallstedt, 2024) from a systems perspective, i.e., across the product's full lifecycle in the social, ecological, and economic dimensions. The outcome of this design method is a list of sustainability criteria captured in an Excel file. The criteria address different aspects of the design, including material selection and geometric parameters, as well as supplier selection and activities such as repair or upgrading. These criteria were later integrated into another design method, a computerized SED design method. This design method uses *digital design experiments* (DDE) (e.g., Martinsson Bonde et al., 2022a) to explore alternative solutions using predefined geometrical and material parameters in the early design phases. In turn, this enables the joint assessment of a set of the *leading sustainability criteria* alongside existing product criteria, e.g., mass and maximum deformation, to explore trade-offs.

These findings highlight the potential of incorporating systemic sustainability criteria into the design process by combining these two different design methods, and provide answers to RQ2.

4.2.3 Identified challenges of integrating sustainability criteria

Although several *leading sustainability criteria* could be integrated, this was not straightforward and required additional resources and time, i.e., method development. Some incompatibilities between the two design methods were also discovered. For example, some parts of the output from LEASA were difficult to integrate appropriately into the analysis (i.e., an incompatibility) and thus also into the design process. This, more specifically, concerns sustainability criteria that did not involve material selection or geometric aspects, which were difficult to incorporate and assess within the DDE. The sustainability criteria also introduced lifecycle thinking into the design process, challenging current ways of working. Furthermore, some sustainability criteria were difficult to incorporate and assess due to a lack of valid information and data.

These findings highlight that integrating different design methods is non-straightforward, and insufficient information and data are available to integrate certain sustainability criteria, which provides answers to RQ1.

4.3 Paper C: From design methods to practice: guiding adoption of sustainable design in manufacturing companies

Paper C reports on the main results from Study 2 and focuses on the development of an adoption approach. This is done by utilizing the qualitative data collected across the case studies from Project I in an abductive way, as described in Section 2.3.2. Paper C is thus a direct continuation and response to the findings from Study 1, which also incorporate the concepts and terminology developed in Paper A. Paper C aimed to answer the following research questions:

- How can managers and design teams be guided in the adoption of new design methods to improve their sustainable innovation capability?

There are three key findings relevant to this thesis, which are described further below: (i) A needs-driven and collaboration-based approach; (ii) Two key insights from testing it across eight case studies.

4.3.1 A needs-driven and collaboration-based approach

A needs-driven and collaboration-based approach is proposed in Paper C to guide the industrial adoption of design methods, addressing three key issues identified in Paper A:

- Design methods need to be integrated into the unique, difficult-to-communicate, and often "fuzzy" design context of design teams, which requires a solid contextual understanding of the company and the design team in question.
- Managers and design teams find it difficult to break down systemic sustainable design challenges into manageable problems in their existing design practices.
- Adoption of new design methods requires design teams to change their current design practices, which gives rise to human-behavioral barriers related to change.

First, a design process logic is used as a tool, or means of communication, since design processes are effective in structuring, governing, and facilitating the fuzzy activity of designing in manufacturing companies. Second, in line with action research, relevant actors are heavily involved throughout the adoption process, raising awareness and providing valuable input to foster a sense of ownership and autonomy, which are critical for motivation and social acceptance of the proposed design methods.

Together, these elements ensure situational design problems and key contextual problems are systematically raised by the designers, allowing them to be addressed appropriately during the adoption process. In turn, ensuring that the new design methods align with the current design context and the design team's needs. Altogether, this provides answers to RQ3.

4.3.2 Two key insights from applying the approach in practice

First, as a result of using the proposed approach, more than 50 *situational design problems* and *contextual problems* were elicited and captured across the formulated design processes in each of the eight case studies part of Study 2 (Section 2.3.2), reflecting the unique design contexts. These were, in turn, used to better understand which design methods to use, and when, where, and how. More than 10 new design methods were successfully identified, selected, adapted, and adopted across the eight case studies. Altogether, across the eight case studies, the adoption approach was shown to support:

- Clarifying and communicating the current and unique design context, establishing a sense of ownership and common language.

- Discussing and highlighting existing sustainability shortcomings and situational design problems in the current design practices, and how these can be addressed by new design methods, creating a sense of urgency and increased awareness.
- Bringing contextual problems to light, enabling appropriate adaptations, and ensuring the design method aligns with the needs of the designers.

This provides clarity in which way the adoption approach facilitates industrial adoption, and provides answers to RQ3.

Second, the approach was also shown to have limitations that can undermine its effectiveness in practice. The approach required expert facilitation, typically organized into three distinct sets of competencies in the literature: *method expertise*, *change-agent expertise*, and *sustainability-change-agent expertise*. These combined qualities, skills, and competencies are comprehensive and not easily taught or acquired, and it is currently unclear whether they can be possessed by a single individual. Moreover, Paper C sheds some light on *cognitive biases* and their potential to negatively influence the long-term impact of this approach.

Altogether, these identified limitations introduce new barriers to industrial adoption, and provide answers to RQ1.

4.4 Paper D: Sharing and managing sustainability information and data in collaborative ecosystems – Insights from testing a novel assessment method with the automotive industry

Paper D reports the main results from both Study 3 and Study 4, focusing on the development of a method for assessing a collaborative ecosystem's ability to share and manage sustainability information and data. This is done by eliciting key issues from the qualitative data collected in Study 3, which is later incorporated as an assessment method used in Study 4. Paper D aimed to answer the following research question:

- How can the assessment of a collaborative ecosystem's ability to appropriately share and manage sustainability information and data be facilitated?

There are five key findings from Paper D relevant to this thesis, which are described in detail below: (i) 14 key assessment criteria; (ii) the incorporation of these 14 key assessment criteria into an interactive assessment method; (iii) key insights from applying the design method in practice; (iv) evaluation of the assessment method; and (v) using the adoption approach to adapt two design methods.

4.4.1 14 key assessment criteria

14 sustainability-contextualized criteria are proposed in Paper C to assess a collaborative ecosystem's ability to share and manage sustainability information and data. These were derived from generalizing key issues and challenges that actors in the automotive industry face and are described in detail in Paper D, along with their relation to sustainable design. These cover conventional aspects of data quality and reliability, as well as issues of trust, shared understanding, data ownership, and agreement on which sustainability information and data to use.

Together, these assessment criteria can act as barriers or as enablers to the industrial adoption of design methods, depending on how they are addressed, and provide answers to both RQ1 and RQ3.

4.4.2 An interactive assessment method

These 14 assessment criteria were also used to develop an interactive, cross-functional assessment that simultaneously promotes shared understanding of key issues in Paper D. This was part of the action research study in Study 4, in which the users of the proposed assessment method were a multidisciplinary team with diverse competencies and experiences who engaged in a facilitated dialogue on these 14 key criteria. The assessment method is described in detail in Paper D, which includes the procedure and guiding templates.

An assessment method for promoting the sharing and management of sustainability information and data is proposed in Paper D, which can be used as a practical means to facilitate the industrial adoption of design methods, and provides answers to RQ3.

4.4.3 Key insights from applying the assessment method in practice

Paper D also presents several insights into the sharing and management of sustainability information and data among value chain actors, which emerged from applying the assessment method across six case studies and seven follow-up interviews. This includes:

- The time and effort that material suppliers spent collecting information and data on sustainable materials were considered excessive. However, some suppliers used standards, which significantly reduced the time. Moreover, it was clear that there must be a shared understanding and agreement about which data is 'valuable'.

- Some of the requested sustainability information and data were considered too vague and ambiguous. To address this issue, activities to improve the qualitative and semantic metrics or scales for some ambiguous data points were proposed.

- The importance of establishing a shared understanding and interpretation of sustainability information and data became clear, with a facilitated face-to-face dialogue between cross-functional teams having certain benefits.
- The need within the collaborative ecosystem to clearly define and agree on the accepted means of collecting data became apparent. There are several standards that can be used; however, each provides a different answer.
- A limited involvement of value chain actors negatively influenced the ability to provide a systemic and complete view of sustainability. For example, excluding certain lifecycle stages and social sustainability perspectives.
- The material suppliers appeared to benefit from the ability to discuss the Value of information and data with the focal company, as providing the required data required significant time and effort. The dialogue around that helped agree on which data to prioritize in the short term and which to consider long-term.

These findings provide further insights into key barriers within sustainability information and data management in a collaborative ecosystem, and provide answers to RQ1.

4.4.4 Evaluation of the assessment method

The assessment method was also evaluated by the participants after it had been used through a Likert-scale questionnaire in Paper D. The evaluation outcomes are appended to Paper D and generally indicate that the method was perceived as useful for assessing the collaborative ecosystems' ability to share and manage sustainability information and data. Altogether, the method was shown to be effective in facilitating and guiding discussions of critical, complex issues related to the current ability to manage sustainability material information and data within the collaborative ecosystem. More specifically, the assessment method supported the cross-functional teams to:

- Assess and understand the current ability to appropriately manage sustainability information and data within the collaborative ecosystem
- Streamline requirements and expectations among these stakeholders concerning the collaborative ecosystem's ability to manage sustainability information and data
- Identify hotspots and propose strategic actions to overcome critical issues concerning the management of sustainability information and data
- Promote both intra- and inter-organizational collaboration among the value chain actors

These findings clarify how the method guides and facilitates the assessment of an ecosystem's ability to share and manage sustainability information and data, and provide answers to RQ2 and RQ3.

4.4.5 Adaptation of two design methods

Two design methods were also adapted using the adoption approach developed in Paper B: (i) the *Sustainable Product Development Workshop Method* (Schulte & Hallstedt, 2018a); and (ii) the assessment method, both of which required contextual adaptation to fit the scope of the *sustainable material data ecosystem* (SMDE) initiative. Examples of the adaptations made include:

- To be material-specific to align with the SMDE initiative's scope. For example, a product criterion related to repair was rephrased to "repairability potential of material [low/medium/high]" to make it a material-oriented data point.
- The terminology used in the methods was adapted to align with the language and terminology used within Company X and the SMDE initiative.
- The two methods were applied in the form of two separate 3-hour workshops to align with the resources available in the SMDE initiative.
- The involvement of stakeholders and representatives during these 3-hour workshops was adapted to align with the scope of the SMDE initiative.
- The two methods were adapted to account for some existing methods and tools identified at Company X.

This highlights the adoption approach's usefulness in identifying specific adaptation issues, and provides answers to RQ3.

4.5 Paper E: A risk analysis method for implementation of additive manufacturing

Paper E addresses some of the barriers and enablers identified in Study 1. Specifically, it addresses information and data management challenges arising from integrating additive manufacturing into established design processes. This is done by developing a risk analysis method that involves mapping workflows into multi-domain matrices, establishing dependencies with associated uncertainty values, and performing risk analysis to determine potential impacts. The method is applied in two industrial case studies in Project II, referred to as *digital design for digital AM* and *digital process for printing with external suppliers*. Moreover, the adoption approach presented in Paper C was used to design these case studies and to provide an industrial context for assessing the risk method's applicability and functionality. As mentioned in Section 2.3.1, empirical data were occasionally collected in Project II to generalize the findings of Study 1, and this includes the two case studies in Paper E. Paper E did not have a research question, but rather the following research objective:

- Propose a prescriptive approach that can assess key challenges related to information and data management challenges arising from integrating additive manufacturing into established design processes, and understand the risks to mitigate them.

There are three key findings from Paper E relevant to this thesis, which are presented in more detail below: (i) The complexity and uniqueness of design processes in manufacturing companies; (ii) The adoption approach's effectiveness in setting up a realistic industrial context that provides a good foundation for testing method applicability and functionality; (iii) Appropriate consideration of information and data management aspects is key for industrial adoption of additive manufacturing.

4.5.1 Complexity and uniqueness of workflows and processes in manufacturing companies

The complexity and uniqueness of workflows and processes in manufacturing companies are highlighted and problematized in Paper E. For example, they are typically highly iterative and dependent on engineers' experience, making them difficult to capture accurately. At the same time, it is seldom obvious how to capture existing workflows and processes with sufficient granularity; instead, they are typically captured in somewhat simplified ways, thereby losing important information, such as tacit knowledge that engineers rely on, which becomes a challenge when mapping existing design processes.

This finding highlights the challenges of capturing and framing existing processes, which are predominantly tacit knowledge among engineers. This provides answers to RQ1, but it rather generalizes previously found answers beyond the context of sustainable design.

4.5.2 Testing method functionality in industrial contexts

The case studies in Paper E were used to identify several industrial challenges related to integrating additive manufacturing into existing processes, thereby identifying the need for the new risk method. The case studies also provided a solid foundation for testing the proposed risk assessment method in an environment closely aligned with industrial practice. In turn, the proposed risk assessment method could be applied across these two distinct industrial settings, which demonstrated its applicability, functionality, and potential for generalization beyond the specific context used in Paper E. Moreover, the design and setup of these industrial case studies were guided by the adoption approach developed in Paper C.

An early version of the adoption approach was shown to be useful for guiding the design and setup of two industrial cases, in turn, used to develop a new risk assessment method and to demonstrate its applicability and functionality. Altogether, this provides answers to RQ3, but rather generalizes previously found answers beyond the context of sustainable design. Moreover, it should be clarified that this risk assessment method was not adopted; rather, it was tested by a researcher serving as a *method expert*, with input from practitioners, to assess its initial applicability and functionality in

an industrial context, which is key for industrial adoption.

4.5.3 Information and data management in additive manufacturing

Appropriate consideration of information and data management aspects is key to the successful integration of additive manufacturing in established workflows or processes. Moreover, the risk analysis showed that the industrialization of additive manufacturing relies on digitalization and digital systems, i.e., on the appropriate management of information and data. In both case studies, the digital process chain and related intellectual property factors were highlighted. In the second case study, it was shown how appropriate software can be used to manage all data access-related challenges throughout the process, thereby helping protect intellectual property and clarify which information is available to whom and to what extent. Additionally, companies that participate in inter-organizational workflows (e.g., the second case study) may have different IT infrastructures, which can lead to interoperability challenges. Such uncertainties are not always visible at the early stages of additive manufacturing implementation.

These findings highlight key challenges and gaps in the management of information and data that hinder the industrialization of additive manufacturing from a workflow and process perspective. In turn, this provides answers to RQ1, but rather generalizes previously found answers beyond the context of sustainable design.

Chapter 5

Synthesis and contributions of this thesis

This chapter summarizes the four key contributions of this thesis, which together advance both knowledge and practice. Together, these contributions form a framework for the industrial adoption of new design methods that guides sustainable design and collaboration, which is illustrated at the end of this chapter in Figure 5.4.

5.1 Contribution 1: A descriptive framework to guide the industrial adoption of design methods

This thesis has proposed a descriptive framework that captures 53 interdisciplinary and interdependent factors influencing the industrial adoption of design methods. The framework comprises eight *core categories.*

- **Category A - Practitioners' understanding of why and how to use design methods:** It relates to designers' understanding of 'why and how' to appropriately use the design methods proposed by *method experts* and/or *developers.*
- **Category B - Method developers' understanding of practitioner needs:** It relates to *method developers*' understanding of designer needs, along with if and how they are translated into the design and development of the new design methods.
- **Category C - Design methods fit into the current design processes:** It relates to the development of the design methods, along with if and how they fit into a company's current design process.
- **Category D - New sustainable design practices:** It relates to the nature and characteristics of new *sustainable design practices* along with

if and how that, in turn, influences the designers, and the new design methods proposed by *method experts* and/or *developers*.

- **Category E - Method experts' understanding of company case and context:** It relates to *method experts'* understanding of the company case and context, along with if and how the new design methods are appropriate and applicable.
- **Category F - Practitioners' design method engagement:** It relates to designers' engagement and how that influences the use of the new design methods proposed by *method experts* and/or *developers*.
- **Category G - Design method synergy and integration:** It relates to whether and how the new design methods proposed by *method experts* and/or *developers* can achieve synergies and integration with other existing and/or new design methods.
- **Category H - Information and data capturing in sustainable design practices:** It relates to the information and data in *sustainable design practices* along with how that, in turn, influences the designers and the new design methods proposed by *method experts* and/or *developers*.

The descriptive framework is presented in Figure 5.1[1], using a network diagram to illustrate the interdependent factors that act as either barriers or enablers. These are directed arrows toward the blue center circle, or another core category, depending on the influence (i.e., direct or indirect). The identified core categories A-H are displayed as yellow boxes. Furthermore, all 53 factors are displayed in Figure 5.1 using a directed arrow with text centered on the line to briefly describe the factor. All positive influences (i.e., enablers) are represented in blue with a plus sign next to the arrow. All negative influences (i.e., barriers) are represented in red with a minus sign next to the arrow. Moreover, the framework captures and displays factors that indirectly influence the center circle, arising from interactions between categories that produce second- and/or third-order effects.

- The framework incorporates process and methodological, organizational, and human-behavioral perspectives, capturing several factors typically scattered across research domains, and **contributes to theory**.
- Moreover, the framework serves as a **practical contribution** by guiding designers and design teams, as well as *method experts* or *method developers*, and design researchers on typical factors (barriers and enablers) that warrant attention in the adoption process and in method development.

[1]The descriptive framework is exhaustive, and the reader is therefore urged to digest it lightly here, and each factor is described in detail in Paper A.

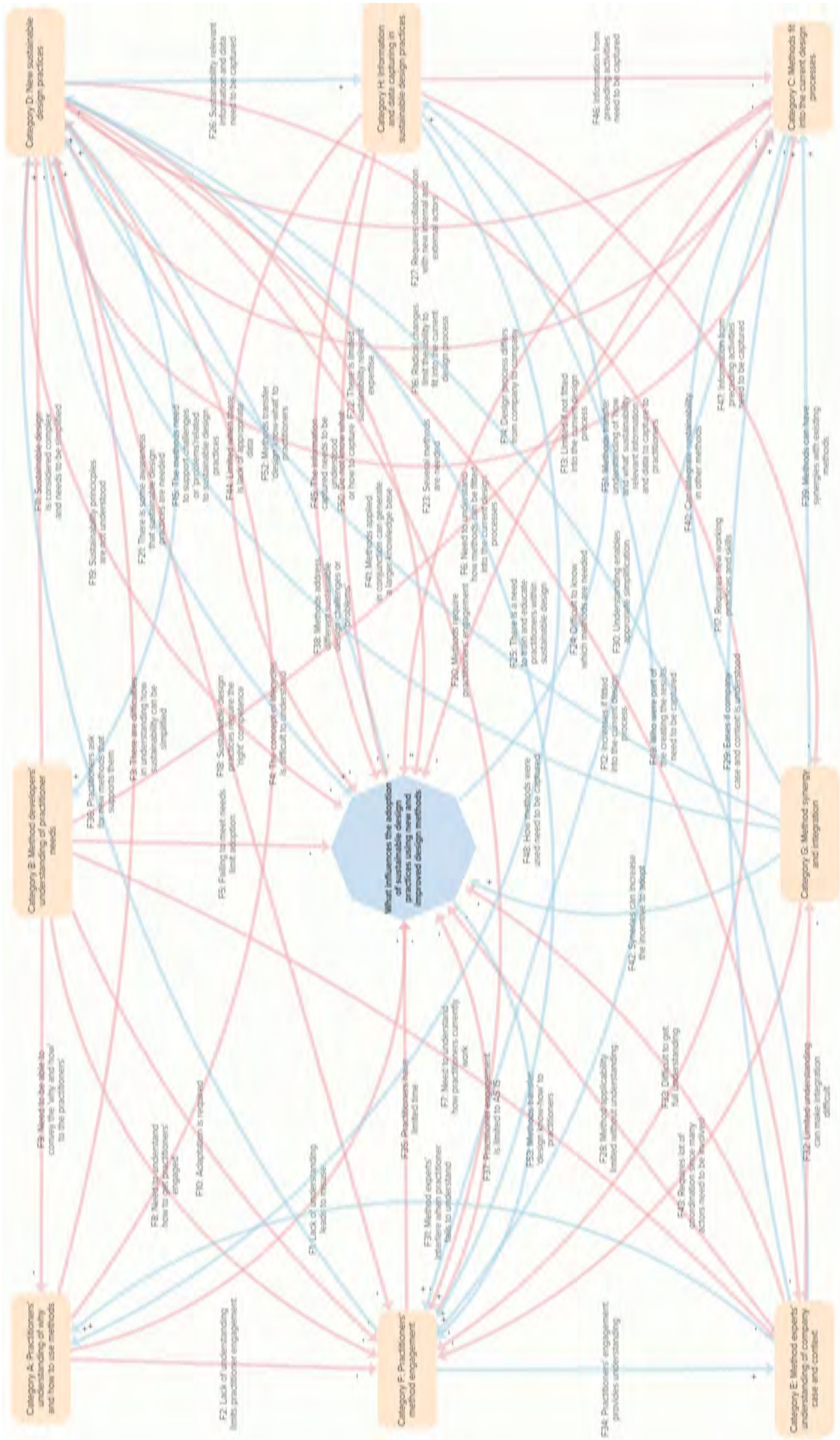


Figure 5.1: The final descriptive framework of the 53 interdisciplinary factors influencing the industrial adoption of new design methods for sustainable design. In the figure, "design methods" is abbreviated to "method".

5.2 Contribution 2: A conceptual model framing design methods as designs

This research has proposed a conceptual model that frames *design methods as designs*. This conceptual model is illustrated in Figure 5.2, where the *Double Diamond* (Design Council, 2005) is used pedagogically to highlight this dual nature and to frame design methods as designed artifacts (i.e., designs). The generic steps of the DRM (Blessing & Chakrabarti, 2009) are also incorporated into this model to highlight this logic.

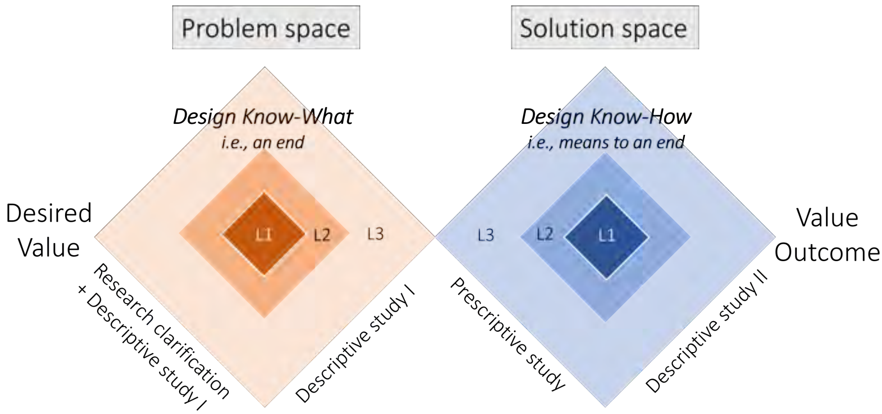


Figure 5.2: Illustration of the *dualism of design methods* where design methods are divided into the *Design know-what* as a 'problem space' and the *Design know-how* as a 'solution space'. This is further divided into the *Situational design problem* (L1), *Situational sub-problems* (L2), and *Contextual problems* (L3).

- This conceptual model introduces the *situational design problem*, and the *dualism of design methods*, which is a **practical contribution**, as it helps bridge the perspectives of process and methodology, organization, and human behavior by introducing terminology and logic that can facilitate designers, *method experts*, and design researchers during the adoption process.
- Moreover, the conceptual model highlights that design methods are value-laden artifacts, or *designs*, i.e., means (solution) to an end (problem). This has significant implications for industrial adoption, since it clarifies that the perceived value of a design method is not necessarily determined by the functional value it provides (the solution) but by the normative value it conveys (the problem), which is often shaped by assumptions or opinions about sustainable design. At the same time, design methods can serve as a means of transferring awareness and understanding of sustainable design through *design know-what*. This enhances understanding of industrial adoption and expands the role of design methods in a sustainability transition, serving as a **theoretical contribution**.

5.3 Contribution 3: An approach to guide design method adoption

This research has proposed a needs-driven and collaboration-based approach to guide and facilitate the industrial adoption of design methods. The adoption approach is highly iterative, promoting close collaboration among key stakeholders, such as *method experts*, designers and design teams, and other stakeholders relevant to the industrial adoption of design methods. Together, this group of people develops a deep, shared understanding of the design context and the situational design problems that require attention. The approach consists of six overarching steps, illustrated and briefly described in Figure 5.3.

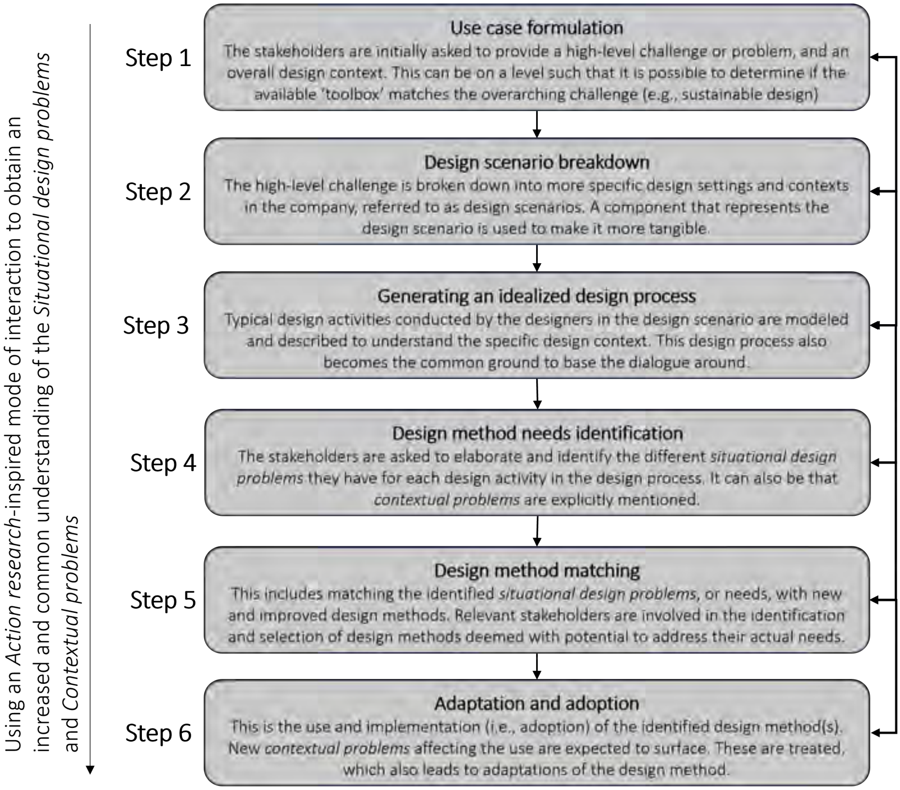


Figure 5.3: The needs-driven and collaboration-based approach. It consists of six generic steps and uses an action research-inspired mode of interacting with the internal stakeholders.

Step 1 focuses on understanding and scoping the systemic sustainable design challenges within the company. **Steps 2 and 3** focus on understanding the designers' specific design context and capturing it visually so it can be communicated and understood by all stakeholders. **Step 4** focuses on understanding the problems the designers face (i.e., *situational design problems* and *contextual* *problems*). An in-depth, shared understanding of such problems serves as a basis for identifying needs and recognizing that current design practices are insufficient to address sustainability appropriately. This is important to capture explicitly and mutually agree upon to frame the need for new design methods. **Step 5** focuses on identifying and selecting candidate design methods that can address the identified design method needs. **Step 6** focuses on adapting the selected design methods using a 'trial-and-error' approach informed by the outcomes from Steps 1-5, so that they can be appropriately adopted.

The needs-driven and collaboration-based approach, *by design*, supports stakeholders in identifying, selecting, and adapting new design methods to meet their needs. **First**, the approach uses a design process logic as a tool, or means of communication, since design processes are effective at structuring, governing, and communicating the fuzzy activity of designing in manufacturing companies. **Second**, an action research-inspired mode of interaction is promoted to involve relevant actors throughout the adoption process, thereby raising awareness and providing valuable input that fosters a sense of ownership and autonomy, which are critical for internal motivation and social acceptance of the proposed design methods. Together, this supports better meeting the individual needs of designers, and thus facilitates the industrial adoption of design methods for sustainable design.

- The approach is thus a **practical contribution**, as it can guide design researchers, designers, design teams, managers, *method experts*, or *method developers* in what, why, where, and how new design methods can be adopted. A detailed and generic guide is available in Appendix I for future use.

5.4 Contribution 4: An assessment method to promote sharing and management of sustainability information and data

This research has proposed an interactive assessment method to promote the sharing and management of sustainability information and data. The intended users of the proposed assessment method are a multidisciplinary team with sufficient competence and experience to provide a qualitative assessment in an interactive format. The method depends on engaging relevant stakeholders across the value chain. This contribution advances both theory and practice. 14 sustainability-contextualized assessment criteria are incorporated in the method, which frame generalized and key issues in sustainability information and data management within collaborative ecosystems.

- These criteria capture both conventional data quality issues and key aspects related to value chain collaboration, together constituting a **theoretical contribution**. These criteria are presented in detail in Paper D.

Moreover, these 14 assessment criteria are integrated into an interactive, cross-functional method that promotes ownership, awareness, and a shared understanding of key issues and ways forward. The method includes procedural logic and intended use, the roles to involve, the overall steps to take and their order, and a guiding template.

- The assessment method thus serves as a **practical contribution** that multidisciplinary teams across organizations can use to promote the sharing and management of sustainability information and data. A generic template is available in Appendix II for future use.

5.5 A framework for the industrial adoption of new design methods that guides sustainable design and collaboration

These four key contributions together form a framework that facilitates the industrial adoption of new design methods, in turn guiding sustainable design and collaboration in the manufacturing industry. Where and how these four contributions can be used in practice to support and facilitate industrial adoption throughout a design method's lifecycle are illustrated in Figure 5.4.

- Contribution 1 (i.e., the descriptive framework) can serve as a specification that defines requirements and prerequisites for industrial adoption. The framework can, in theory, be used throughout the process but is proposed to be introduced and considered during method development, i.e., *industrial adoption as a requirement*.

- Contribution 3 (i.e., the adoption approach) can guide the adaptation and adoption process, addressing the dilemma presented in Figure 1.2. The adoption approach is therefore proposed for use when a new design method is mature and has been tested and proven to function in practice.

- Contribution 4 (i.e., the assessment method) can promote the sharing of sustainability information and data, thereby facilitating the adoption of new design methods. The assessment method depends on a set of desired information and data as input and is therefore proposed for use in the later stages to provide the necessary information and data that the new design method requires.

- Contribution 2 (i.e., the conceptual model framing design methods as designs) is not illustrated in the figure, as it is embedded in the descriptive framework and the adoption approach.

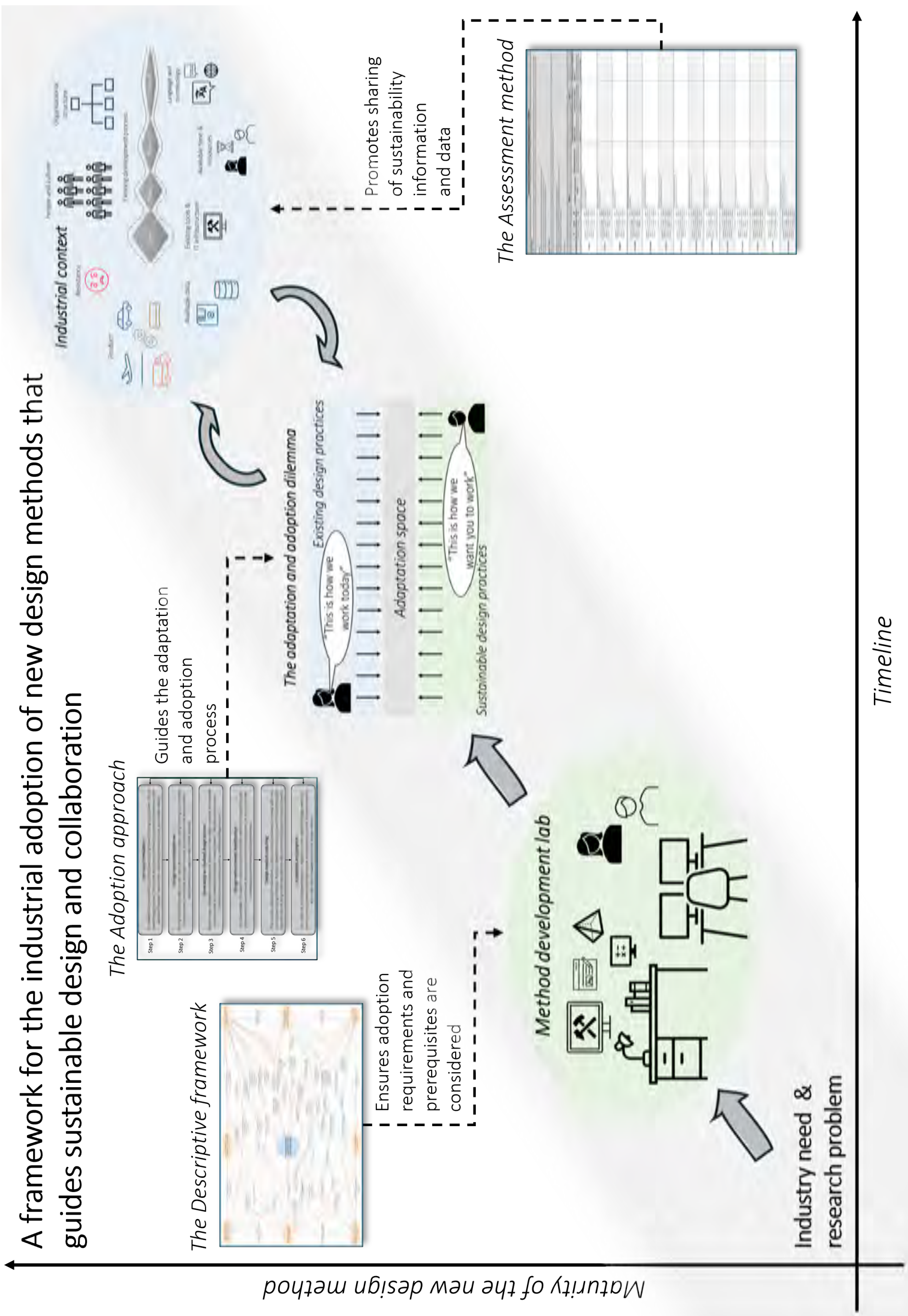


Figure 5.4: A compiled framework for the industrial adoption of new design methods that guides sustainable design and collaboration. The grey area illustrates a simplified design method lifecycle going from industry need & research problem to industrial adoption. The two axis suggests the design method mature as time passes. The key contributions are mapped to highlight where and how they can support industrial adoption as the new design method matures.

Chapter 6

Discussion

First, the key results of this research are discussed, organized by the three research questions; here, aspects of novelty are also discussed. Following this, the key contributions of this thesis are discussed in terms of their validity, thereby suggesting the need for future work.

6.1 Barriers influencing the industrial adoption of new design methods for sustainable design

- RQ1: *What barriers influence the industrial adoption of new design methods for sustainable design?*

RQ1 aimed to generate new insights into the key barriers to industrial adoption. The research question was intentionally broad to reflect the exploratory, interdisciplinary scope of this research, and the answer will be divided into four overarching themes or problem areas, as presented in the sub-sections below.

6.1.1 Industrial adoption of new design methods and the influence of human-behavioral aspects

This research has empirically shown across all four studies that adopting a new design method for sustainable design will require some degree of change in how designers work today. This narrative has also been raised in previous research (e.g., Lee, 2021; Hallstedt et al., 2020; Julier and Kimbell, 2019; Eppinger, 2011). At the same time, it is well acknowledged that achieving change is typically challenging (Oreg et al., 2011). Similarly, in the design literature, López-Mesa and Bylund (2011) acknowledges that "people do not want to change their way of working". This issue was also figuratively depicted in Figure 1.2, where a design researcher promotes a theoretically ideal way to practice sustainable design and pushes for this change from one side. On the other side, the time-pressured designer pushes to maintain as much of the status quo as possible.[1] This subsection, therefore, discusses and problematizes the broader issue of resistance to industrial adoption from a human-behavioral perspective by drawing on three theories or concepts from the management domain.

Several scholars in the design domain have acknowledged that design methods are often *prescriptive*[2], though to varying extents (Gericke et al., 2022). To recap from Section 3.5, Wallace (2011), for example, states that design methods are "a prescriptive plan of action by which a class of design tasks is tackled". Eder (1998) similarly states that design methods are "prescriptive knowledge as advice about designing ('know-how')", whereas Gericke et al. (2022) stated, "a method is a kind of promise: follow the outlined steps and you should be able to get a certain kind of result". This also aligns with the findings of this research (see Factor 53 in the descriptive framework). In parallel, there has been much research on "work design" and "motivational theory", where **work autonomy** is highlighted as a key enabler for motivation and social acceptance (Hackman and Oldham, 1976; Deci et al., 2017). However, the prescriptive nature of design methods imposes constraints on how designers should work, thereby clashing with their ability to achieve a generally desired *work autonomy*. In turn, this can explain some of the initial resistance to the proposal of new design methods. This has been reported on before (e.g., Rossi et al., 2016), but not framed through the lens of *work autonomy*.

Furthermore, overcoming initial resistance to change is challenging and typically requires the recipient to have an intrinsic need for the change, i.e., clearly perceive the **value of changing** (Burnes, 2004; Oreg et al., 2011). Kotter (1995), for example, argues that there needs to be a "sense of urgency" before change initiatives can gain traction, and Burnes (2004) refers to this as a "felt need". Lewin et al. (1947) instead referred to this as a stage of achieving 'unfreezing' before the desired change can be made:

> "To overcome this inner resistance an additional force seems to be required, a force sufficient to 'break the habit,' to 'unfreeze' the custom."

And Oreg et al. (2011), for example, state:

> "A key determinant of whether change recipients will accept or resist change is the extent to which the change is perceived as personally beneficial or harmful."

On the other hand, the overall need and challenge of clarifying a design method's value has been raised in design literature (e.g., López-Mesa and Bylund, 2011). The complexity, or challenge, of clarifying and perceiving the value of a design method is further emphasized and addressed in Paper A, specifically through

[1]The author wishes to emphasize that there is not always necessarily an inner resistance to change (Oreg et al., 2011; Burnes, 2015).

[2]Prescribe is here defined as "to tell someone what they must have or do, or to make a rule of something" (Cambridge, 2026b).

the *dualism of design methods*. This concept proposes that design methods are value-laden artifacts, and that the value must be adopted — but it is seldom (yet). More specifically, in Study 1, it was observed that the value of design methods was best experienced through their use, which becomes a paradox, and in Paper A, this is referred to as the *dualism of design methods paradox*.

To add further complexity, a set of **cognitive biases** towards change was also presented in Table 3.3, in Section 3.7. In essence, these highlight that **individuals tend to prefer maintaining the status quo despite the benefits of change**. This provides an additional explanation for why design methods are typically perceived as requiring too much time and effort, as there must be a clear perceived value to justify even considering change, and that active facilitation is needed to overcome initial resistance and achieve social acceptance (Burnes, 2004; Oreg et al., 2011).

Furthermore, Paper A highlighted that there are *cognitive biases* towards sustainability (i.e., opinions and assumptions) that can amplify this issue and occasionally lead to "cherry-picking" of which sustainability aspects to include. To add further nuance, an additional set of previously identified cognitive biases that can shape social acceptance and motivation is presented in Table 6.1, with brief descriptions and sources. In essence, several biases can arguably influence how individuals interpret, understand, prioritize, and accept sustainability initiatives. In turn, helping to clarify why barriers such as a perceived lack of appropriate data, insufficient time and effort, perceived value, and excessive complexity arise. However, assessing these in detail is beyond the scope of this thesis, and they are included to provide perspectives that receive less attention in the design literature on industrial adoption. This will be briefly discussed in Section 6.4.2, as cognitive biases can limit the effectiveness of the adoption approach. Moreover, *cognitive biases* have, to some extent, been reported and studied in the context of sustainable design and sustainability decision-making (e.g., Korteling et al., 2023; Klotz et al., 2018; Gould, 2018; Weber, 2017).

Table 6.1: Cognitive biases that can be linked to how individuals interpret, understand, prioritize, and accept sustainability initiatives.

Cognitive bias	*Brief description and source*
Anchoring bias	Some individuals tend to accept, rely on, or bias their decisions based on the first information they receive (Tversky & Kahneman, 1974).
Bandwagon effect	Some individuals tend to adopt beliefs and behaviors the more they have been adopted (Asch, 1951; Simon, 1954; Colman, 2003).
Conformity bias	Some individuals tend to adjust their thinking and behavior to the group standard (Cialdini & Goldstein, 2004).
Egocentric bias	Some individuals tend to rely too heavily on their own point of view or preferences, failing to consider others' perspectives (Ross & Sicoly, 1979; Moore & Kim, 2003).
Egocentric empathy gap	Some individuals tend to project their own preferences, values, behaviors, or beliefs onto others (Van Boven et al., 2000; Van Boven & Loewenstein, 2003).
False consensus effect	Some individuals tend to overestimate how much others agree with them and how common their own behavior and choices are among others (Ross et al., 1977).
Focusing illusion	Some individuals tend to focus too much on one or a limited set of aspects/factors when estimating the future outcome, or making decisions (Schkade & Kahneman, 1998; Loewenstein & Angner, 2003; Kahneman et al., 2006).
Framing bias, or *effect*	Some individuals tend to base their decisions on how information is framed rather than on the facts themselves (Tversky & Kahneman, 1981).
Frequency bias/effect, or the *Illusory truth effect* (not the same as *frequency illusion*)	Some individuals tend to increase their belief in, or make valid, certain statements or facts when they are frequently exposed to them (Hasher et al., 1977; Schwartz, 1982).
Hyperbolic discounting	Some individuals tend to prefer or prioritize decisions/choices that yield smaller rewards now over those that yield larger rewards later (Loewenstein & Prelec, 1992; Laibson, 1997; Green & Myerson, 2004).
Optimism bias (see also *Planning fallacy*)	Some individuals tend to overestimate the probability of positive outcomes and underestimate the probability of negative outcomes (Kahneman & Tversky, 1977; Weinstein, 1980; Lovallo & Kahneman, 2003; O'Sullivan, 2015).
Priority heuristic	Some individuals tend to base their decisions on a single dominant piece of information (Brandstätter et al., 2006).
Projection bias	Some individuals tend to overestimate how much their future state will share their current preferences or values (Laibson, 1997; Loewenstein et al., 2003; Loewenstein & Angner, 2003).
Quantification bias, or the *McNamara Fallacy*	Some individuals tend to overestimate the influence of quantitative data, metrics, or values higher than qualitative data when making decisions (Fischer, 1970).
Representativeness heuristic	Some individuals tend to assign subjective probabilities to outcomes or events based on how they represent or resemble a similar situation or stereotype, rather than their statistical probability (Kahneman & Tversky, 1972).
Use of *heuristics* (not a specific cognitive bias as such, see also Bounded Rationality)	Some individuals tend to use heuristics, simplifications, or 'rules-of-thumb' to speed up the decision-making process when dealing with complex problems, occasionally leading to non-beneficial or non-optimal outcomes (Simon, 1969; Tversky & Kahneman, 1974).

6.1.2 The contextual complexity of design method adoption

Throughout this research, the contextual complexity of adopting design methods is highlighted, and industrial adoption cannot be treated as a 'plug-and-play' activity. This has been raised before; Eder (1998), for example, states that "the method must be adapted to problem and situation, adapted to different kinds of product and peculiarities of the enterprise". Gericke et al. (2020) also highlights the need for contextual adaptation and refers to this context as the *method ecosystem*. Paper A elaborates on this and frames it as the *situational design problem paradox*. This paradox claims that, in theory, design methods are limited in their transferability or applicability because *situational design problems* resemble *design problems* and are unique. Such a paradox, in turn, indicates that the use and applicability of proposed design methods are limited, since the *situational design problem* will differ each time, and the design method will always require some adaptation.

In addition, a designer's or design team's design context not only varies, but it is also difficult to specify, pinpoint, and communicate effectively and efficiently (Maffin, 1998; Ottosson, 2003; Gericke et al., 2020 & 2021). Similar issues were raised in Papers A, B, C, D, and E, and are a key barrier: the individual designer's knowledge of the fuzzy design context is not readily available to the *method expert*, and serious effort must be devoted to acquiring this knowledge, which also requires some degree of domain- and context-specific competence. Moreover, concrete examples of necessary and typical adaptations made in this research were presented in Papers A, B, C, D, and E to clarify this complexity. Lastly, many of the required adaptations are contextual, or unique, and the results (i.e., problems and solutions) of these activities will be difficult to generalize beyond that context; hence, the name used to frame them is *contextual problems*.

6.1.3 Managing sustainability information and data

This research has also emphasized the need for appropriate sustainability information and data management. No clear or distinct definition has yet been provided, but the ISO8000 standard (ISO, 2026) defines data quality management as:

> "Data quality management covers all aspects of data processing, including creating, collecting, storing, maintaining, transferring, exploiting, and presenting data to deliver information."

Within this broad topic, Paper A generally found that there is:

- A lack of access to sustainability information and data early in the design process.
- A lack of understanding of what sustainability information and data are required.

- A lack of shared understanding and interpretation of sustainability information and data among collaborating actors.
- A lack of time and resources to retrieve and/or generate appropriate sustainability information and data.

In Paper B, this is further concretized, where, e.g., information and data on the social conditions of workers in raw-material extraction and downstream activities are lacking. It was also challenging to integrate sustainability criteria such as 'repairability' and 'minimizing safety risks' appropriately into the evaluation of concepts. At the same time, it is worth acknowledging that the issue of sustainability integration from a 'method functionality' perspective has been addressed elsewhere (e.g., Al Handawi et al., 2021; Martinsson Bonde et al., 2025).

Nevertheless, building on the early findings in Papers A and B, Paper D later elaborates on the overarching issue of sustainability information and data, proposing 14 key criteria to frame general and key issues in sustainability information and data management. Each of these criteria can, in turn, be seen as a barrier to the industrial adoption of design methods if considered inadequately. For example, low *actuality* or *accuracy* of data can undermine the validity or usefulness of the design method's outcomes. Paper D also introduces 'soft' aspects that arise when several actors in the value chain need to share and manage information and data together. For example, intellectual property issues related to data sharing, misaligned expectations, and trust. Similar aspects are also raised in Paper E, but in the context of additive manufacturing. At the same time, many such aspects related to managing sustainability information and data have been reported in previous studies (e.g., Schöggl et al., 2024; Booker, 2012), but nevertheless remain a key barrier to the industrial adoption of design methods.

6.1.4 The need for effective facilitation and expertise

Throughout this research, three sets of competencies have been identified as relevant to facilitate the industrial adoption of design methods. In Paper A, the notion of a *method expert* is first explicitly stated, but the skills of such an individual are evident across all papers. In Paper C, two additional roles are introduced, i.e., *Change agents*, and *Sustainability change agents.* These three roles are elaborated upon below.

First, *method experts* with sufficient competence and experience in the use and application of one (or more) of the available design methods, such that they can be modified and adapted appropriately. It is also beneficial if this individual is aware of the consequences of different modifications and can effectively communicate their effects on outcomes to the stakeholders involved. Additionally, this individual should possess experience and competence in *designerly ways of knowing, thinking, and acting* (Cross, 1982, 2023a & 2024), enabling them to effectively understand and contextualize the new design method according to the manufacturing company's internal terminology and design logic. This was shown empirically in this research. However, this type of competence and skill has been elaborated upon in the context of design in the literature (e.g., Eder, 1998 & 2009; Dorst, 2008; Stacey et al., 2025).

Second, *change agents* with leadership qualities who can manage and drive the change have been identified in the literature (e.g., Ford and Ford, 2010; R. Thomas and Hardy, 2011). There are several studies that have elaborated on how change comes about differently and can, or should, be managed (e.g., Dunphy and Stace, 1993; Kotter, 1995; Burnes, 1996; By, 2005; Van de Ven and Sun, 2011). To give an idea, some facets are presented below.[3]

- Dunphy and Stace (1993) present a matrix that divides the characteristics of the change into two dimensions: (i) different leadership styles used to manage change, and (ii) the scale of change.
- Burnes (1996) reviews a set of strategies for managing change and categorizes them as either emergent (bottom-up) or planned (top-down).
- By (2005) breaks down a set of models or strategies for change and divides the characteristics of these as: (i) how change comes about (e.g., planned, or emergent), (ii) rate of occurrence (e.g., discontinuous, or incremental), and (iii) scale of change.

Burnes (1996) does, however, criticize the idea of simply adopting any prescribed approach and highlights that there is no "one best way" to manage organizational change, indicating that managing change in itself requires certain competencies and skills. Furthermore, R. Thomas and Hardy (2011) also raise concerns about the use of *change agents*, since considerable responsibility rests on the individual. Moreover, facilitating stakeholder involvement is also a skill in itself, and has been elaborated upon in other literature (e.g., Kanter, 1981; Moran and Brightman, 2000; Burnes et al., 2018).

Third, *sustainability change agents* who can drive and manage sustainability-focused change initiatives have also been identified in the literature (e.g., Daly et al., 2025). Such individuals are argued to require qualities such as systems thinking, normative, and interpersonal skills (Wiek et al., 2011; Missimer and Connell, 2012; Redman and Wiek, 2021; Ayers et al., 2023). Boucher et al. (2018), for example, raise several key challenges that environmental managers commonly face. Such as being isolated, having vague strategic targets, and not having a clear role in decision-making, and most likely also applies to *sustainability change agents*.

Altogether, this becomes a key barrier, since the identified qualities, skills, and competencies are comprehensive and not easily taught or acquired, hindering adoption. Moreover, it is unclear if these capabilities can be possessed by a single individual in manufacturing organizations.

[3]The intent here is not to provide an extensive summary, but to humbly communicate that change management is a research domain and skill in its own right.

6.2 The role of new design methods in sustainability transitions

- RQ2: *In what ways can new design methods support manufacturing companies in their sustainability transition?*

RQ2 aimed to capture how design methods, potentially beyond industrial adoption, can support manufacturing companies in their sustainability transition. In turn, this research has found four distinct ways in which design methods can support manufacturing companies in their sustainability transition.

6.2.1 Design methods as means for improving management of sustainability information and data

This research has shown that design methods can be an effective means of improving the management of sustainability information and data. In Paper A, this was evident by *Factor 51 - Design methods transfer understanding of 'how and what' sustainability-relevant information and data to capture to practitioners*. It was observed that design methods can guide which information and data are required to adopt that specific design method. This can, in turn, support the identification of which information and data, ideally, should be available to conduct different design activities, e.g., sustainability assessments. Furthermore, the use of prescriptive design methods supports the alignment and streamlining of terminology and the understanding of concepts and terms used in sustainable design, and was also elaborated upon in Paper A. This is beneficial from a value chain perspective, where multiple actors hold different views on what sustainability means and the terms used. Later, this was incorporated into the assessment method proposed in Paper D. Lastly, the use of design methods can help address traceability issues by (often) enabling the tracking and storage of results in a digital format. At the same time, design methods have generally been shown to improve record-keeping, traceability, and accountability for stakeholders involved in decision-making (Araujo et al., 1996; Eder, 1998 & 2009). Altogether, the use of design methods is argued to enhance an organization's information and data management capabilities.

6.2.2 Design methods as means for transferring design know-what

This research has shown that design methods can be an effective means for raising awareness and understanding of *sustainable design*. In Paper A, this was evident by *Factor 52 - design methods transfer 'design know-what' to practitioners*. It was observed that design methods can serve as a means to both clarify and transfer knowledge about what represents *sustainable design*, i.e., what knowledge needs to be produced or what 'problems' need to be solved to appropriately integrate sustainability. This was conceptualized in Paper A using the *situational design problem*, and that design methods can convey and/or transfer:

- What *situational design problems* are relevant to the *design problem*.
- What knowledge about the *design problem* is relevant to produce.

This argument is further exemplified below using two established design methods, Zwicky (1967)'s method for generating concepts and Pugh (1981)'s method for evaluating and screening concepts.

- The design method by Zwicky (1967) conveys to designers that it is typically effective to find potential solutions to the *design problem* by generating and combining several different alternative sub-concepts, or sub-solutions, for each previously identified sub-function, or sub-problem. This is effective because, for example, it can lead to insights (i.e., knowledge) about which combinations of sub-solutions work and which set of alternative solutions could solve the *design problem*. It is possible to phrase this *situational design problem* as 'how to generate different alternative solutions to the *design problem*'.
- The design method by Pugh (1981) conveys to designers that it is typically effective to compare different concepts, or solutions, systematically against previously identified criteria, or 'sub-problems'. This is effective because, for example, it can yield insights (i.e., knowledge) on how to improve and potentially merge ideas, solutions, or sub-solutions to create even better solutions that address the *design problem*. It is possible to phrase this *situational design problem* as 'how to systemically compare and screen alternative solutions against the criteria, or sub-problems'.

The *design know-what* can play an important role in a change management context since it is crucial that the change recipients perceive the value of the new design method, or have a 'felt need', as discussed in Section 6.1.1.

6.2.3 Design methods as means for transferring design know-how

This research has shown that design methods can be an effective means for raising awareness and understanding of how to practice *sustainable design*. In Paper A, this was evident by *Factor 53 - design methods transfer 'design know-how' to practitioners*. It was observed that design methods can serve as a means of transferring knowledge about how to carry out key activities in *sustainable design*, i.e., a recipe for producing relevant knowledge or solving 'problems'. This was conceptualized in Paper A using the *situational design problem*, and that design methods can convey and/or transfer:

- How to solve *situational design problems* relevant to the *design problem*.
- How to produce knowledge relevant to the *design problem*.

This proposal aligns with the current view of design methods as prescriptive 'know-how' (e.g., Eder, 1998; Gericke et al., 2022).

Following the two examples in Section 6.2.2, the two design methods also indicate how different *situational design problems* can be 'solved', or how relevant knowledge can be generated. However, these two *situational design problems* can also be solved in different ways. For example, a Zwicky (1967)'s morphological approach can be adopted in different ways, such as by pen and paper, Excel-based tools, computerized software (e.g., Martinsson Bonde et al., 2022b), or as a *digital design experiment* set up as in Paper B. How such a design method depends on what type of *design problem* the designer faces.

6.2.4 Design methods as collaborative and interactive means

This research has shown that design methods can be an effective means for structuring and governing knowledge exchange among multidisciplinary (or cross-functional) teams, promoting both intra- and inter-organizational collaboration. This was raised in Paper A, not by a specific factor but through the three factors above (F51, F52, and F53), in which design methods, in essence, provide a platform for intra- and inter-organizational knowledge exchange and alignment on key issues. The author's co-supervisor, long ago, provided a summarizing statement that captures this:

> "Design methods are especially relevant in the sense that they put the issue on the otherwise quite busy agenda."

These elements were later used in Paper D, as the assessment method 'by design' incorporated such interactive formats to address issues related to shared understanding, ownership, and agreeing on ways forward in the context of sustainability information and data management. Lastly, a statement from one of the participants will be used to frame this clearly:

> "The obvious feeling is that we have been able to build a better connection among the people involved in this initiative. The assessment method forced people within company A to discuss. For example, the guy from the lab, the people from sustainability, and the people from functions Y and Z were discussing for the first time, all together in the same place. Also, they were aligning, and that was not easy to do outside the predefined context provided by the assessment method. Secondly, it has initiated reflection, especially on the people driving sustainability within the company."

At the same time, it is worth acknowledging that some argue the opposite, i.e., that design methods should preferably not require cross-functional involvement (e.g., Vicente and Camocho, 2024). A collaborative setting is nevertheless essential for achieving, e.g., knowledge transfer, shared understanding, and ownership, and similar findings have been reported, suggesting that design methods should be designed to enable cross-functional collaboration (e.g., Ritzén and Lindahl, 2001; Rossi et al., 2016). Moreover, a collaborative setting also aligns with the arguments discussed in Section 6.1.1.

6.3 Facilitating the adoption of new design methods for sustainable design

- RQ3: *How can the industrial adoption of new design methods for sustainable design be facilitated?*

RQ3 aimed to capture relevant insights and provide practical guidance to improve industrial adoption. This research best answers the research question through the elements incorporated into the adoption approach and the assessment method, which are presented and discussed in the following sub-sections.

6.3.1 Adhering to 'industrial adoption as a requirement' during method development

This research has proposed a descriptive framework that captures 53 interdisciplinary and interdependent factors influencing the industrial adoption of design methods, presented in Paper A. The framework captures both barriers and enablers, highlighting key factors related to industrial adoption; these elements have been discussed in the subsection above. At the same time, the framework's 53 factors can facilitate industrial adoption if they are considered together during method development, i.e., *industrial adoption as a requirement*. There are other extensive lists that can support the development of new design methods and industrial adoption (e.g., Rossi et al., 2016; Vicente and Camocho, 2024), along with Tables 3.1 and 3.2. However, the descriptive framework proposed in this research incorporates process and methodological, organizational, and human-behavioral perspectives, capturing several factors typically scattered across research domains, and is therefore argued to constitute a novel contribution.

6.3.2 Facilitating adoption using a needs-driven and collaboration-based approach

This research has proposed a novel approach to facilitate the adaptation and industrial adoption of design methods. The approach supports design researchers, or *method experts*, in better understanding the organizational context in which the design method will be used, thereby enabling appropriate adaptation. The approach also supports design researchers, or *method experts*, in incorporating key aspects typically raised in the change management literature. More specifically, promoting close collaboration and stakeholder involvement to foster ownership and autonomy in the adoption process. The adoption approach comprises six distinct steps that combine action research and a design process logic to ensure that the new design methods fit the current design context and the design team's needs. Moreover, the approach also incorporates the conceptual model in its terminology and design. The adoption approach has been continuously improved across the cases in Project I and Project II, with early versions used and reported in Papers B and E, and the final format presented in Paper C, later used in Paper D. Altogether, the approach supports:

- Clarification and communication of the current and unique design context to the stakeholders involved, establishing a sense of ownership and common language
- Discuss and highlight the existing sustainability shortcomings and situational design problems in the current design practices, and how these can be addressed by new design methods, creating a sense of urgency and increased awareness
- Bringing the contextual problems to light, enabling appropriate adaptations, and ensuring the design method aligns with the needs of the designers

Furthermore, empirical results from applying the approach across eight cases in Project I are available in Appendix III.

To summarize, the approach provides a recipe and structure for design researchers or method experts to follow, supporting them in identifying key *contextual problems* while actively adhering to key aspects of change. In turn, this answers RQ3.

Lastly, prior research has emphasized the need for contextual adaptation to better meet designers' needs, as well as the need for practical guidance (e.g., Vicente and Camocho, 2024; Gericke et al., 2021 & 2020; Faludi et al., 2020; Jagtap et al., 2014), where some research efforts have used an action research-inspired approach to enhance industrial adoption (e.g., Hallstedt and Isaksson, 2017; Brones et al., 2021). However, although practical guidance exists in the literature (e.g., Ritzén and Lindahl, 2001; Lindemann, 2002; Ernzer and Birkhofer, 2002; O'Hare et al., 2010; Brones et al., 2021; Lavrsen et al., 2022), the author nevertheless argues that the proposed adoption approach offers novel and practical knowledge on this topic that can be used to guide the industrial adoption of design methods.

6.3.3 Promoting sharing and management of sustainability information data across collaborating value chain actors

This research has proposed a novel assessment method to facilitate the industrial adoption of design methods. Moreover, the lack of appropriate sustainability information and data has been a recurring issue throughout this research, which requires both intra- and inter-organizational efforts, as lifecycle data is scattered across actors in the value chain. To address this complex issue, an assessment method was proposed in Paper D. It is interactive and provides a structure and platform for multidisciplinary teams to discuss critical and complex issues related to current capabilities for managing sustainability information and data, and agree on ways forward. The assessment method consists of: (i) 14 sustainability-contextualized assessment criteria that frame generalized and key issues in sustainability information and data management within collaborative ecosystems; (ii) a procedural logic and intended use, the roles to involve, the overall steps to take and their order, and a guiding template, which integrates these 14 assessment criteria into an interactive, cross-functional method. In turn, this promotes ownership, awareness, and a shared understanding of key issues and ways forward. The assessment method was evaluated in Paper D using three separate data collection methods, and was shown to support:

- Assessing and understanding the current ability to appropriately manage sustainability information and data in the collaborative ecosystem
- Streamlining requirements and expectations among key stakeholders concerning the collaborative ecosystem's ability to manage sustainability information and data
- Identifying hotspots and proposing strategic actions to overcome critical issues concerning the management of sustainability information and data
- Promoting both intra- and inter-organizational collaboration among value chain actors

To summarize, the assessment method provides a recipe and structure for designers, managers, and other practitioners to identify key sustainability information and data management issues, as well as ways forward. This can increase access to sustainability information and data, facilitating the industrial adoption of design methods and answering RQ3.

Lastly, similar approaches to this type of assessment have been proposed (e.g., Schöggl et al., 2017; Schulte and Hallstedt, 2018a), and previous research has raised similar issues related to information and data management (Schöggl et al., 2024; Trevisan et al., 2022; Brinkmann and Wynn, 2025a & 2025b). However, these are extensive, and it is unclear which of these are relevant to address in the context of collaborative ecosystems. In turn, this bundle of elements (i) and (ii) is therefore argued to offer novel and practical knowledge on this topic through *theory elaboration* (Ketokivi & Choi, 2014), while also addressing an identified research gap (e.g., Aryee et al., 2025; Geissdoerfer et al., 2026).

6.4 Validity and novelty of the key findings

The validity of the key findings of this research will be further discussed in this section. First, the descriptive framework and the conceptual model are discussed. Last, the two prescriptive findings will be discussed.

6.4.1 Validity of the descriptive framework and the conceptual model

The descriptive framework and the conceptual model were developed as part of Study 1, which employed a rigorous inductive analysis using *Glaserian Grounded Theory*. As described in Section 2.3.1.3, several strategies were employed to enhance the validity of these findings, and all of these strategies will not be repeated explicitly. Nevertheless, the analysis used a large sample of qualitative empirical data from multiple cases in Study 1 (Table 2.2), complemented by theoretical sampling from data collected in seminars with additional companies. Furthermore, insights and findings from Project II and EWB-SWE efforts are incorporated to strengthen the *external validity* of Study 1's findings. Together, these also enable *triangulation* and strengthen the overall validity of the findings (Creswell, 2014; Eisenhardt, 1989). It is worth acknowledging that part of these results has been reported in publications that are not appended to this thesis (e.g., Mallalieu et al., 2022; Hajali et al., 2023; Mallalieu et al., 2024), but support generalizing the results further and strengthening their *external validity* (Säfsten & Gustavsson, 2020). Lastly, the findings have also been compared with previous literature to further strengthen their validity (Säfsten & Gustavsson, 2020).

Furthermore, as mentioned in Section 2.3.1.3, one main limitation of the adopted research approach and the findings is the reliability and repeatability. Elements of *hermeneutics* and *pragmatism* have been adopted and thus also play a significant role in the collection and analysis of data. This was therefore approached by ensuring transparency in the documentation of data collection and analysis. The raw data and analysis are accessible, allowing external scrutiny of the procedure and revisiting the source data. The researcher's bias and role have also been presented transparently to further clarify how they may have influenced the results of this research (Creswell, 2014). Furthermore, the correspondence criteria aimed to support the assignment of appropriate codes. However, it is difficult to justify assigning the same codes if another researcher had conducted the analysis. The codes generated during the *Glaserian Grounded Theory* analysis, on the other hand, have been 'approved' by the co-authors. The co-authors, more specifically, compared the raw data to the assigned code to ensure appropriate correspondence.

6.4.2 Validity of the needs-driven and collaboration-based adoption approach

The adoption approach was developed in an *abductive* manner (Dorst, 2011; Säfsten and Gustavsson, 2020), allowing continuous refinement of its format based on insights gained from testing it across several case studies. As described in Section 2.3.2, the eight case studies in Project I served as the core input and involved four manufacturing companies, which supports the generalizability of the findings, i.e., the *external validity* (Säfsten & Gustavsson, 2020). In turn, the approach is argued to be applicable to manufacturing companies beyond the ones involved in this study. Furthermore, early versions of the approach have also been used and tested across other industrial contexts:

- In Project II, the approach was used across several case studies, whereas two were reported on in Paper E. This study involved other manufacturing companies, and the focus was on additive manufacturing. Moreover, part of these results have, as mentioned, been reported in Mallalieu et al. (2022) and Hajali et al. (2023).

- In EWB-SEW, the approach was used in some efforts. However, the focus was on design methods for humanitarian engineering. These results have been reported on in Jonasson and Pettersson (2023) and Mallalieu et al. (2024).

Altogether, these efforts enhance the generalizability of the adoption approach, indicating its applicability across different types of design methods.

Later, in Study 4, the approach was tested and evaluated in its final form and in a more operational setting as part of an action research study at an automotive OEM, described in Section 2.3.4. Figure 6.1 illustrates the overarching activities carried out, divided into two main blocks. Block A, which focused on contextualization by studying existing design processes and identifying key contextual issues using the adoption approach. This later fed into Block B, which focused on key activities carried out in the project to develop the *sustainable material data ecosystem* (SMDE). Examples of generalized key issues that were identified are marked in orange. As illustrated in Figure 6.1 and evident in Paper D, Block B used two adapted design methods: (i) the *Sustainable Product Development Workshop Method* (Schulte & Hallstedt, 2018a); and (ii) the assessment method.

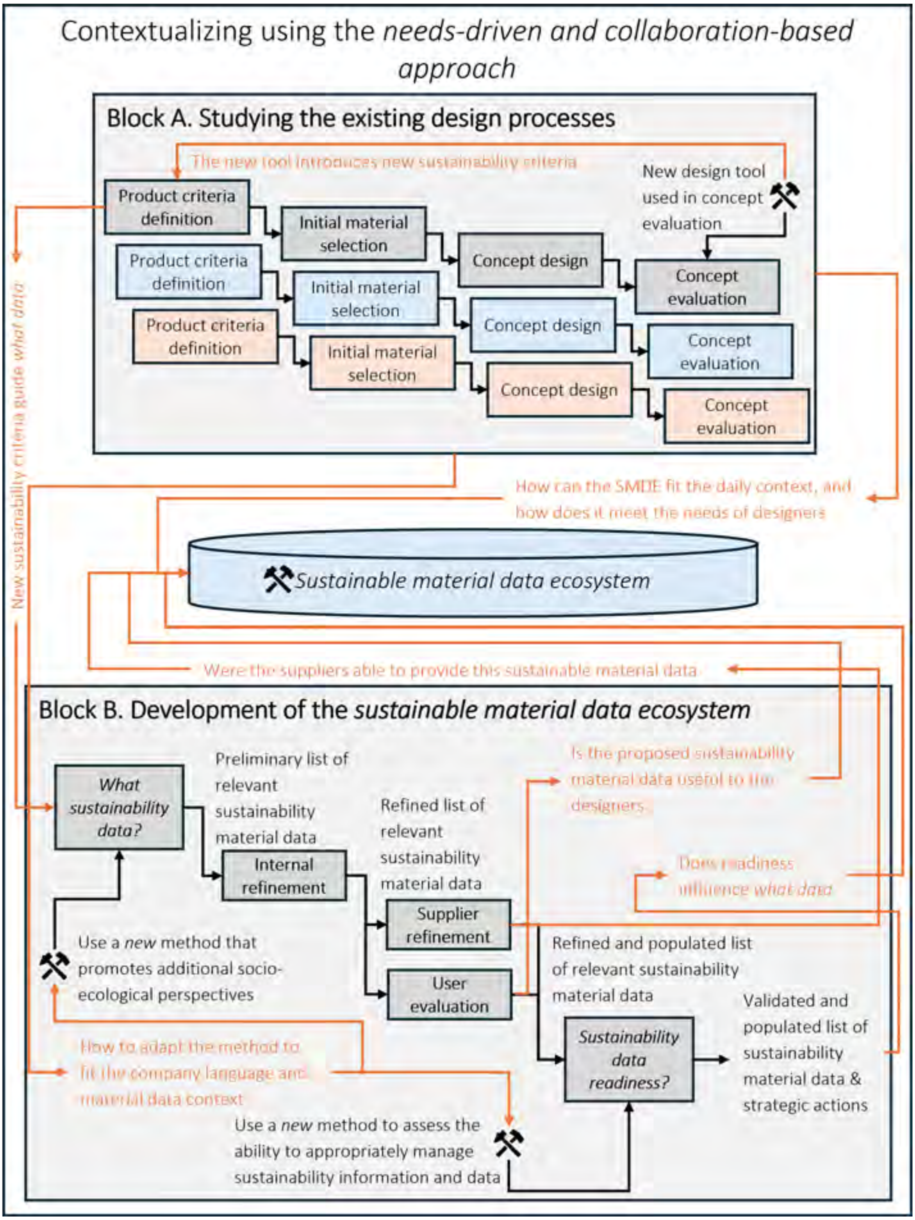


Figure 6.1: The parallel activities carried out in Study 4 in black, along with the insights and considerations that surfaced during the study in red. Four design methods, or tools, were considered and are indicated by a hammer icon.

In summary, applying the adoption approach yielded several key insights into the development and future adoption of the SMDE.[4] These insights are

[4]This research project is ongoing, hence it is not yet clear if and how the SMDE will be implemented in practice.

illustrated in Figure 6.1, indicating the usefulness of the adoption approach in raising key issues that support adaptation efforts. Some of these are briefly described below.

- The adoption approach supported the identification of a new internal tool at Company X to be considered in the development of the SMDE. The internal tool, more specifically, clarifies which sustainability criteria are used to evaluate the sustainability performance of concepts, guiding what data is desired.

- The adoption approach supported the adaptation and adoption of two design methods in Project V. The use of these, in turn, provided several key insights used as input to the development of the SMDE, such as which data is mature enough to integrate into the SMDE.

- The approach effectively highlighted that designers' design processes and needs differ significantly and influence how the SMDE, in theory, meets them. In turn, efforts to better understand how the SMDE can fit into these began.

Altogether, Study 2 and Study 4 provide strong support for the claim that the approach appropriately addresses issues related to communication, raising awareness, identifying which design methods to use and where, and making appropriate modifications to those design methods. The approach has supported the appropriate adaptation and adoption of more than 10 design methods and provided key insights for the development of a completely new design tool (i.e., the SMDE).

At the same time, as Study 4 allowed the author to test the adoption approach in a more operational setting, some limitations were identified.

- It was generally challenging to involve stakeholders who were occupied with prioritized operational activities, as activities related to the industrial adoption of a new design method were considered less urgent.

- Study 4 was situated in a research project, and not an implementation project. This influenced the time horizon and roadmap. And, in turn, also how and what contextual problems were addressed.

- The time required to fully contextualize is substantial, and in large organizations, contextual differences can vary widely. Within Company X, for example, design processes are expressed in significantly different ways depending on the designer's position within the organizational structure.

Furthermore, although the adoption approach has been successful in guiding adoption, it is generally difficult to claim that it will guarantee long-term use of those design methods, as it provides no clarity on whether social acceptance and ownership have been achieved. At the same time, it is generally difficult to claim that any approach will guarantee long-term success, as it is influenced by many unpredictable factors, such as *cognitive biases*, which are discussed in Papers A, C, and Section 6.1.1 and highlight how this can influence individuals' acceptance. Moreover, the design methods adopted in Study 2 and Study 4 were championed by design researchers or method experts as part of research projects (i.e., Projects I, II, and V). This was raised in Section 6.1.4 and can be seen as a limitation.

Nevertheless, the proposals by Lewin (1946 & 1947) and Coch and French (1948) are generally considered valid today, and an action research-oriented approach has historically been proven effective in facilitating change (Kanter, 1985; Kotter, 1995; Oreg et al., 2011; Burnes, 2015; Deci et al., 2017). For example, close involvement creates a heightened sense of urgency and ownership of the problem, internalizing the need for the intended change, which positively affects attitude and internal motivation for the change initiative. The adoption approach similarly emphasizes democratic values and the participation of relevant stakeholders in the change process to influence the adaptation, thereby promoting work autonomy. Moreover, research on the industrial adoption of design methods has observed similar positive effects by using an action research-inspired approach (e.g., Hallstedt and Isaksson, 2017; Brones et al., 2017 & 2021). In turn, the validity of the approach is largely established in prior research. However, prior research provides evidence, but testing the approach through a longitudinal study in an operational setting is needed to better understand the long-term impact of the adoption approach.

6.4.3 Validity of the assessment method

The assessment method was developed and evaluated in three phases; each phase will be discussed, followed by a summary of the two main limitations.

First, the 14 key assessment criteria were derived from the issues and challenges identified during Study 3. Several activities were conducted with automotive industry stakeholders, including interactive workshops and semi-structured interviews. The main limitation is that only one automotive OEM was involved, which can influence the generalizability of these key issues and challenges. However, seven companies representing different parts of the automotive value chain were involved, and these other six actors, for example, collaborate with other OEMs and can be argued to help ensure that challenges relevant beyond the automotive OEM are raised, thereby enhancing generalizability (Säfsten & Gustavsson, 2020). A total of five researchers active in this topic participated in the data collection and analysis to improve rigor (Creswell, 2014), and *inter-rater reliability* (Säfsten & Gustavsson, 2020). Lastly, literature assisted this process in parallel by streamlining terminology and strengthening external validity (Creswell, 2014; Säfsten and Gustavsson, 2020).

Second, the 14 assessment criteria were integrated into an interactive, cross-functional method. This was done as part of an action research study at an automotive OEM, where data were collected through more than 30 informal interviews and work meetings with relevant stakeholders in Study 4 to understand this organizational context. However, the generalizability of these findings (contextual problems and adaptations) is limited, as they are specific to one OEM's context. At the same time, action research was an active choice, as the study aimed to obtain the deep understanding necessary to contextualize and adapt the assessment method, i.e., test the adoption approach.

Third, an adapted version of the assessment method was applied across six case studies, and three methods were used to collect qualitative data for evaluation.

- Outcomes were captured during the workshop through qualitative observations by the academic participants (Creswell, 2014) and through visual recordings using the guiding template.
- The participants were asked to evaluate the method using a Likert-scale questionnaire.
- Six follow-up interviews were conducted across the six case studies to evaluate the assessment method, and one interview was conducted with the project manager.

Based on the *qualitative observations* and follow-up interviews, the assessment was generally effective in facilitating and guiding discussions of critical, complex issues related to the current ability to manage sustainability material information and data within the collaborative ecosystem. Moreover, the questionnaire indicated that the method was perceived as useful for assessing the collaborative ecosystems' ability to share and manage sustainability information and data. In turn, these three sources *triangulate* the empirical findings and enhance the *internal validity* of the elements included in the assessment method (Eisenhardt, 1989; Säfsten and Gustavsson, 2020). The assessment method needs to be tested in additional contexts before its generalizability and *external validity* can be assessed beyond the situational context of this study. However, the study involved six parallel case studies with different first-tier material suppliers, thereby supporting the generalizability of the assessment method (Säfsten & Gustavsson, 2020). It is possible to argue that the procedural logic and intended use, the roles to involve, the overall steps to take, and their order, and the guiding template are applicable in contexts beyond the one in Study 4. As mentioned, similar approaches to this type of assessment have been proposed (e.g., Schöggl et al., 2017; Schulte and Hallstedt, 2018a), and previous research has raised similar issues (Schöggl et al., 2024; Trevisan et al., 2022; Brinkmann and Wynn, 2025a & 2025b). In turn, this strengthens the *external validity* (Creswell, 2014; Säfsten and Gustavsson, 2020).

There were two main limitations when testing the assessment method: (i) The case studies only included a limited set of value chain actors, i.e., an OEM acting as the focal company and first-tier material suppliers, and lacked perspectives from, e.g., downstream actors; (ii) The case studies only involved value chain actors from the automotive industry and one OEM, or focal company, which can influence the generalizability of this study. Future work should, therefore, focus on testing the assessment method with a larger set of value chain actors across industries. In turn, this can improve its generalizability beyond the context studied, enhancing its *external validity* and alignment with its intended use and purpose.

Chapter 7

Conclusion and future research

This chapter presents the conclusions, explains how the findings contribute to new knowledge, and outlines future work.

7.1 Conclusions

This research aimed to increase understanding of what can limit adoption, how to facilitate adoption, and how new design methods can increase an organization's ability to design more sustainable solutions. The intent was to explore this and provide new insights by simultaneously considering three perspectives typically scattered among research domains: process and methodology, organization, and human behavior. Moreover, three research questions were formulated to guide this work, and the brief answers to these are presented below.

The first part of this aim is addressed by providing answers to RQ1: *What barriers influence the industrial adoption of new design methods for sustainable design?* Given the results from this research, the answers are divided into four overarching themes:

- This research has shown empirically that design researchers must consider human-behavioral aspects when proposing new design methods, where three established concepts have been utilized to ground and clarify this barrier: *work autonomy*, *Stakeholder involvement and collaboration*, and *cognitive biases.*

- This research has shown empirically and clarified that there is always a need to adapt new design methods to the targeted context, providing concrete examples of how this is a complex, paradoxical, non-trivial, time-consuming activity that requires practical guidance.

- This research has shown empirically that current sustainability information and data management capabilities of manufacturing companies are insufficient to effectively and efficiently adopt new design methods, and that this requires improved intra- and inter-organizational collaboration.

- This research has shown that at least three distinct sets of competencies are necessary to facilitate the industrial adoption of new design methods, i.e., method expertise, change-agent expertise, and sustainability-change-agent expertise.

This research found that role of new design methods in sustainability transitions are: (i) means for improving the information and data management capabilities of an organization; (ii) means for transferring *design know-what* to practitioners; (iii) means for transferring *design know-how* to practitioners; and (iv) means for providing support and structure intra- and inter-organizational collaboration. In turn, this answers RQ2: *In what ways can new design methods support manufacturing companies in their sustainability transition?*, thus fulfilling the third part of the research aim, and expands on the role that a design method can play in manufacturing companies' sustainability transitions.

The results of this research also provide answers to RQ3: *How can the industrial adoption of new design methods for sustainable design be facilitated?* fulfilling the remaining aim of this research. First, this research has identified 53 interdisciplinary factors that, if considered appropriately, can facilitate industrial adoption of new design methods. Second, this research has shown that appropriate *consideration of organizational and human-behavioral perspectives* can facilitate the industrial adoption of new design methods. More specifically, by combining action research with a design process logic into a needs-driven and collaboration-based approach, ensuring the new design methods are adapted and grounded in their unique design context. Third, this research has shown that the sharing and management of sustainability information and data in a collaborative ecosystem can be guided using an interactive assessment method. In turn, this can (long-term) improve access to sustainability data, facilitating industrial adoption of new design methods.

7.2 Scientific contributions

This thesis has also generated new knowledge relevant to the industrial adoption of new design methods, which, in turn, is useful to design researchers and designers seeking to adopt them.

- This research has proposed a descriptive framework that captures 53 interdisciplinary and interdependent factors influencing the industrial adoption of design methods. The framework incorporates process and methodological, organizational, and human-behavioral perspectives, capturing several factors typically scattered across research domains, and is a novel contribution to knowledge.

- To the best of the author's knowledge, design methods' ability transfer *design know-what* to practitioners is a novel contribution, whereas their ability to improve the information and data management capabilities of an organization, transferring *design know-how* to practitioners, and support and structure intra- and inter-organizational collaboration are touched upon by previous literature.

- This research has shown that the conceptual model that frames *design methods as designs*, using the *situational design problem*, and the *dualism of design methods* can facilitate adoption. It supports bridging different process and methodological, organizational, and behavioral perspectives to better understand barriers to industrial adoption. The model also clarifies why adoption is challenging and how adaptation can be effectively managed. To the best of the author's knowledge, this conceptual model is a novel contribution.

- This research has shown that a needs-driven and collaboration-based approach can facilitate the industrial adoption of new design methods by better aligning with designers' individual needs. To the best of the author's knowledge, combining action research and a design process logic to achieve this is a novel contribution.

- This research has shown that the assessment method comprising 14 key assessment criteria, a procedural logic, and a guiding template can be used to assess the ability to share and manage sustainability information and data in collaborative ecosystems. In turn, facilitating the industrial adoption of new design methods. To the best of the author's knowledge, this bundle of elements is a novel contribution.

7.3 Future work

The results from this research pave the way for future research.

- The descriptive framework is based on an inductive analysis, in which 53 factors influencing industrial adoption were identified. However, these factors have not been tested to determine whether, when appropriately considered, they entail successful adoption. A future study is necessary to examine these factors individually in a more deductive way to better confirm their significance.

- The needs-driven and collaboration-based approach requires further testing in a fully operational environment, where a longitudinal study is necessary to examine its long-term effects.

- The needs-driven and collaboration-based approach will also benefit from being tested by industrial representatives rather than by design researchers. There are, for example, practical gaps in how this adoption process is initiated when it is not part of a research project. Moreover, this will also provide an opportunity to obtain further clarity on the three identified competencies that require further investigation.

- The assessment method requires further testing with additional automotive OEMs, the involvement of additional value chain actors across the product's lifecycle, and potentially in other sectors to better understand its generalizability and applicability beyond the studied context.

References

ACARE. (2022). Fly the Green Deal. Retrieved April 8, 2024, from https://www.acare4europe.org/news/fly-the-green-deal/

Åge, L.-J. (2011). Grounded theory methodology: Positivism, hermeneutics, and pragmatism. *Qualitative Report*, *16*(6), 1599–1615.

Ahmad, S., Wong, K. Y., Tseng, M. L., & Wong, W. P. (2018). Sustainable product design and development: A review of tools, applications and research prospects. *Resources, Conservation and Recycling*, *132*, 49–61.

Al Handawi, K., Andersson, P., Panarotto, M., Isaksson, O., & Kokkolaras, M. (2021). Scalable set-based design optimization and remanufacturing for meeting changing requirements. *Journal of Mechanical Design*, *143*(2), 021702.

Almefelt, L. (2005). *Requirements-driven product innovation methods and tools reflecting industrial needs* [Doctoral dissertation, Chalmers University of Technology].

Araujo, C., Benedetto-Neto, H., Campello, A., Segre, F., & Wright, I. (1996). The utilization of product development methods: A survey of uk industry. *Journal of Engineering Design*, *7*(3), 265–277.

Archer, B. (1979). Design as a discipline. *Design studies*, *1*(1), 17–20.

Arkes, H. R., & Blumer, C. (1985). The psychology of sunk cost. *Organizational Behavior and Human Decision Processes*, *35*(1), 124–140.

Arnold, J. E. (1956). Creativity in engineering. *SAE Transactions*, *64*, 17–23.

Aryee, R., Kanda, W., Geissdoerfer, M., & Kirchherr, J. (2025). Circular ecosystems: Past, present, and future research directions. *Journal of Industrial Ecology*, *29*(4), 1364–1381.

Asch, S. E. (1951). Effects of group pressure upon the modification and distortion of judgments.

Asimow, M. (1962). *Introduction to design*. Prentice-Hall.

Auernhammer, J., & Roth, B. (2021). The origin and evolution of stanford university's design thinking: From product design to design thinking in innovation management. *Journal of Product Innovation Management*, *38*(6), 623–644.

Ayers, J., Missimer, M., & Bryant, J. (2023). Intrapersonal capacities for sustainability: A change agent perspective on the 'inner dimension' of sustainability work. *Sustainability Science*, *18*(3), 1181–1197.

Baldassarre, B., Keskin, D., Diehl, J. C., Bocken, N., & Calabretta, G. (2020). Implementing sustainable design theory in business practice: A call to action. *Journal of Cleaner Production*, *273*, 1–17.

Banach, S. J., & Ryan, A. (2009). The art of design: A design methodology. *Military review*, *89*(2), 105–115.

Bengtsson, M., Alfredsson, E., Cohen, M., Lorek, S., & Schroeder, P. (2018). Transforming systems of consumption and production for achieving the sustainable development goals: Moving beyond efficiency. *Sustainability science*, *13*, 1533–1547.

Bhander, G. S., Hauschild, M., & McAloone, T. (2003). Implementing life cycle assessment in product development. *Environmental Progress*, *22*(4), 255–267.

Blessing, L. T., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer London. https://doi.org/10.1007/978-1-84882-587-1

Blizzard, J. L., & Klotz, L. E. (2012). A framework for sustainable whole systems design. *Design Studies*, *33*(5), 456–479.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320.

Bocken, N. M., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production*, *65*, 42–56.

Boks, C. (2006). The soft side of ecodesign. *Journal of Cleaner Production*, *14*(15-16), 1346–1356.

Booker, J. (2012). A survey-based methodology for prioritising the industrial implementation qualities of design tools. *Journal of Engineering Design*, *23*(7), 507–525.

Borgue, O., Paissoni, C., Panarotto, M., Isaksson, O., Andreussi, T., & Viola, N. (2021). Design for test and qualification through activity-based modelling in product architecture design. *Journal of Engineering Design*, *32*(11), 646–670.

Boucher, J., Jenny, C., Plummer, Z., & Schneider, G. (2018). How to avoid pigeonholing the environmental manager? *Sustainability*, *10*(7), 2538.

Brandstätter, E., Gigerenzer, G., & Hertwig, R. (2006). The priority heuristic: Making choices without trade-offs. *Psychological review*, *113*(2), 409.

Brinkmann, J. T., & Wynn, D. C. (2025a). Aspects of information maturity in design and development. *Research in Engineering Design*, *36*(2), 8.

Brinkmann, J. T., & Wynn, D. C. (2025b). Handling preliminary engineering information: An interview study and practical approach for clarifying information maturity. *Systems*, *13*(8), 674.

Broman, G. I., & Robèrt, K.-H. (2017). A framework for strategic sustainable development. *Journal of Cleaner Production*, *140*, 17–31.

Broman, G. I., & Robèrt, K.-H. (2025). Operative system for strategic sustainable development—coordinating analysis, planning, action, and use of supports such as the sustainable development goals, planetary boundaries, circular economy, and science-based targets. *Sustainable Development*, *33*(4), 4759–4774.

Brones, F., de Carvalho, M. M., & de Senzi Zancul, E. (2017). Reviews, action and learning on change management for ecodesign transition. *Journal of Cleaner Production*, *142*, 8–22.

Brones, F., Zancul, E., & Carvalho, M. M. (2021). Insider action research towards companywide sustainable product innovation: Ecodesign transition framework. *International Journal of Managing Projects in Business*, *14*(1), 150–178.

Brundtland, G. H. (1987). Our common future—call for action. *Environmental Conservation*, *14*(4), 291–294. https://doi.org/10.1017/S0376892900016805

Buchanan, R. (1992). Wicked problems in design thinking. *Design issues*, *8*(2), 5–21.

Burnes, B. (1996). No such thing as... a "one best way" to manage organizational change. *Management decision*, *34*(10), 11–18.

Burnes, B. (2004). Kurt lewin and the planned approach to change: A re-appraisal. *Journal of Management Studies*, *41*(6), 977–1002.

Burnes, B. (2015). Understanding resistance to change–building on coch and french. *Journal of Change Management*, *15*(2), 92–116.

Burnes, B., Hughes, M., & By, R. T. (2018). Reimagining organisational change leadership. *Leadership*, *14*(2), 141–158.

By, R. T. (2005). Organisational change management: A critical review. *Journal of Change Management*, *5*(4), 369–380.

Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production*, *14*(15-16), 1420–1430.

Cambridge. (2024). Adoption - English meaning. Retrieved April 13, 2024, from https://dictionary.cambridge.org/dictionary/english/adoption

Cambridge. (2026a). Facilitating - English meaning. Retrieved May 4, 2026, from https://dictionary.cambridge.org/sv/ordbok/engelska/facilitating

Cambridge. (2026b). Prescribe - English meaning. Retrieved May 6, 2026, from https://dictionary.cambridge.org/dictionary/english/prescribe

Carlsson, S., Mallalieu, A., Almefelt, L., & Malmqvist, J. (2021). Design for longevity-a framework to support the designing of a product's optimal lifetime. *Proceedings of the Design Society*, *1*, 1003–1012.

Cash, P., Isaksson, O., Maier, A., & Summers, J. (2022). Sampling in design research: Eight key considerations. *Design studies*, *78*, 101077.

Ceschin, F., & Gaziulusoy, İ. (2019). *Design for sustainability: A multi-level framework from products to socio-technical systems*. Routledge.

Ceschin, F., & Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design studies*, *47*, 118–163.

Charmaz, K. (1996). The search for meanings - grounded theory. In *Rethinking methods in psychology* (pp. 27–49). Sage Publications.

Chebaeva, N., Lettner, M., Wenger, J., Schöggl, J.-P., Hesser, F., Holzer, D., & Stern, T. (2021). Dealing with the eco-design paradox in research and development projects: The concept of sustainability assessment levels. *Journal of Cleaner Production*, *281*, 125232.

Cialdini, R. B., & Goldstein, N. J. (2004). Social influence: Compliance and conformity. *Annu. Rev. Psychol.*, *55*(1), 591–621.
Coch, L., & French, J. R. (1948). Overcoming resistance to change. *Human relations*, *1*(4), 512–532.
Colman, A. (2003). Group think: Bandwagon effect. *Oxford dictionary of psychology*, *77*.
Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
Cross, N. (1982). Designerly ways of knowing. *Design studies*, *3*(4), 221–227.
Cross, N. (1992). *Research in design thinking*. Delft University Press.
Cross, N. (1999). Design research: A disciplined conversation. *Design issues*, *15*(2), 5–10.
Cross, N. (2007). Forty years of design research. *Design studies*, *1*(28), 1–4.
Cross, N. (2023a). Design thinking: What just happened? *Design Studies*, *86*.
Cross, N. (2023b). *Engineering design methods: Strategies for product design*. John Wiley & Sons.
Cross, N. (2024). Design as a form of intelligence. In *Designerly ways of knowing and thinking* (pp. 119–126). Springer London.
Da Silva, S., Gupta, R., & Monzani, D. (2023). Highlights in psychology: Cognitive bias.
Daalhuizen, J., & Cash, P. (2021). Method content theory: Towards a new understanding of methods in design. *Design Studies*, *75*, 101018.
Daly, E. M., Gould, R. K., & Lagun Mesquita, P. (2025). Champion, activist or intrapreneur? a typology of change agents for corporate sustainability. *Corporate Social Responsibility and Environmental Management*, *32*(5), 6301–6316.
Deci, E. L., Olafsen, A. H., & Ryan, R. M. (2017). Self-determination theory in work organizations: The state of a science. *Annual Review of Organizational Psychology and Organizational Behavior*, *4*, 19–43.
Design Council. (2005). The Double Diamond - A universally accepted depiction of the design process. Retrieved April 9, 2024, from https://www.designcouncil.org.uk/our-resources/the-double-diamond/
Dorst, K. (2006). Design problems and design paradoxes. *Design issues*, *22*(3), 4–17.
Dorst, K. (2008). Design research: A revolution-waiting-to-happen. *Design Studies*, *29*(1), 4–11.
Dorst, K. (2011). The core of 'design thinking'and its application. *Design studies*, *32*(6), 521–532.
Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem–solution. *Design studies*, *22*(5), 425–437.
Dunphy, D., & Stace, D. (1993). The strategic management of corporate change. *Human Relations*, *46*(8), 905–920.
Eder, W. E. (1998). Design modeling-a design science approach (and why does industry not use it?) *Journal of Engineering Design*, *9*(4), 355–371.
Eder, W. E. (2009). Why systematic design engineering? *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, *49057*, 513–522.

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, *14*(4), 532–550.

Engineers Without Borders Sweden. (2026). Engineers without borders sweden. https://www.ewb-swe.org/

Eppinger, S. (2011). The fundamental challenge of product design. *Journal of Product Innovation Management*, *28*(3), 399–400.

Ernzer, M., & Birkhofer, H. (2002). Selecting methods for life cycle design based on the needs of a company. *DS 30: proceedings of DESIGN 2002, the 7th international design conference, Dubrovnik*, 1305–1310.

European Commision. (2021). Horizon Europe. Retrieved April 8, 2024, from https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

European Environment Agency. (2017). Circular by design — Products in the circular economy. Retrieved February 26, 2026, from https://www.eea.europa.eu/en/analysis/publications/circular-by-design

European Union. (2024). Regulation (EU) 2024/1781 of the European Parliament and of the Council. https://eur-lex.europa.eu/eli/reg/2024/1781/oj

Faludi, J., Hoffenson, S., Kwok, S. Y., Saidani, M., Hallstedt, S. I., Telenko, C., & Martinez, V. (2020). A research roadmap for sustainable design methods and tools. *Sustainability*, *12*(19).

Faste, R. (1994). Ambidextrous thinking. *Innovations in mechanical engineering curricula for the 1990s*.

Festinger, L. (1957). A theory of cognitive dissonance. *Stanford University Press*.

Fischer, D. H. (1970). Historians' fallacies: Toward a logic of historical thought.

Flick, U. (2007). Sampling, selecting and access. *Designing qualitative research*, 25–35.

Ford, J. D., & Ford, L. W. (2010). Stop blaming resistance to change and start using it. *Organizational dynamics*, *39*(1), 24.

Fuller, R. B. (1957). A comprehensive anticipatory design science. *Royal Architectural Institute of Canada*, *34*(8), 357–61.

Geis, C., Bierhals, R., Schuster, I., Badke-Schaub, P., Birkhofer, H., et al. (2008). Methods in practice–a study on requirements for development and transfer of design methods. *DS 48: Proceedings DESIGN 2008, the 10th International Design Conference, Dubrovnik, Croatia*, 369–376.

Geissdoerfer, M., Kanda, W., & Kirchherr, J. (2026). Conceptualizing circular ecosystems: An analysis of 45 definitions. *Business Strategy and the Environment*, *35*(2), 2368–2394.

Gericke, K., Adolphy, S., Qureshi, A. J., Blessing, L., & Stark, R. (2021). Opening up design methodology. *The Future of Transdisciplinary Design: Proceedings of the Workshop on "The Future of Transdisciplinary Design", University of Luxembourg 2013*, 3–14.

Gericke, K., Eckert, C., Campean, F., Clarkson, P. J., Flening, E., Isaksson, O., Kipouros, T., Kokkolaras, M., Köhler, C., Panarotto, M., et al. (2020).

Supporting designers: Moving from method menagerie to method ecosystem. *Design Science*, *6*.

Gericke, K., Eckert, C., & Stacey, M. (2022). Elements of a design method–a basis for describing and evaluating design methods. *Design Science*, *8*.

Gomez, A. P., Kretzschmar, M., Paetzold-Byhain, K., & Isaksson, O. (2025). A team of three: The role of generative ai in the development of design automation systems for complex products. *Proceedings of the Design Society*, *5*, 309–318.

Gould, R. (2018). *The individual human side of supporting sustainable design beginners* [Doctoral dissertation, Blekinge Tekniska Högskola].

Green, L., & Myerson, J. (2004). A discounting framework for choice with delayed and probabilistic rewards. *Psychological Bulletin*, *130*(5), 769.

Gregory, S. A. (1966). Design science. In *The design method* (pp. 323–330). Springer.

Hackman, J. R., & Oldham, G. R. (1976). Motivation through the design of work: Test of a theory. *Organizational Behavior and Human Performance*, *16*(2), 250–279.

Hajali, T., Mallalieu, A., Brahma, A., Panarotto, M., Isaksson, O., Stålberg, L., & Malmqvist, J. (2023). Information flow analysis enabling the introduction of additive manufacturing for production tools - insights from an industrial case. *Proceedings of the Design Society*, *3*, 2315–2324.

Hallstedt, S. I., & Isaksson, O. (2017). Material criticality assessment in early phases of sustainable product development. *Journal of Cleaner Production*, *161*, 40–52.

Hallstedt, S. I., Isaksson, O., Nylander, J. W., Andersson, P., & Knuts, S. (2023a). Sustainable product development in aeroengine manufacturing: Challenges, opportunities and experiences from gkn aerospace engine system. *Design Science*, *9*.

Hallstedt, S. I., Isaksson, O., & Öhrwall Rönnbäck, A. (2020). The need for new product development capabilities from digitalization, sustainability, and servitization trends. *Sustainability*, *12*(23), 10222.

Hallstedt, S. I., Villamil, C., Lövdahl, J., & Nylander, J. W. (2023b). Sustainability fingerprint-guiding companies in anticipating the sustainability direction in early design. *Sustainable Production and Consumption*, *37*, 424–442.

Hasher, L., Goldstein, D., & Toppino, T. (1977). Frequency and the conference of referential validity. *Journal of verbal learning and verbal behavior*, *16*(1), 107–112.

Herzberg, F. I. (1966). Work and the nature of man.

Isaksson, O., Keski-Seppälä, S., & Eppinger, S. D. (2000). Evaluation of design process alternatives using signal flow graphs. *Journal of Engineering Design*, *11*(3), 211–224.

Isaksson, O., Kossmann, M., Bertoni, M., Eres, H., Monceaux, A., Bertoni, A., Wiseall, S., & Zhang, X. (2013). Value-driven design–a methodology to link expectations to technical requirements in the extended enterprise. *INCOSE International Symposium*, *23*(1), 803–819.

Isaksson, O., Wynn, D. C., & Eckert, C. (2023). Design perspectives, theories, and processes for engineering systems design. In *Handbook of engineering systems design* (pp. 1–47). Springer.

ISO. (2026). Iso 8000-1:2022(en) data quality — part 1: Overview. Retrieved May 6, 2026, from https://www.iso.org/obp/ui/#iso:std:iso:8000:-1:ed-1:v1:en

Jagtap, S., Warell, A., Hiort, V., Motte, D., & Larsson, A. (2014). Design methods and factors influencing their uptake in product development companies: A review. *DS 77: Proceedings of the DESIGN 2014 13th International Design Conference*.

Johansson, G. (2002). Success factors for integration of ecodesign in product development: A review of state of the art. *Environmental Management and Health*, *13*(1), 98–107.

Jonasson, A., & Pettersson, S. (2023). *A feasibility study process for humanitarian engineering systematically increasing the social impact for a swedish ngo*.

Jones, J. C. (1992). *Design methods*. John Wiley & Sons.

Julier, G., & Kimbell, L. (2019). Keeping the system going: Social design and the reproduction of inequalities in neoliberal times. *Design Issues*, *35*(4), 12–22.

Kahneman, D., Krueger, A. B., Schkade, D., Schwarz, N., & Stone, A. A. (2006). Would you be happier if you were richer? a focusing illusion. *Science*, *312*(5782), 1908–1910.

Kahneman, D., & Tversky, A. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology*, *3*(3), 430–454.

Kahneman, D., & Tversky, A. (1977). Intuitive prediction: Biases and corrective procedures.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decisions under risk. *Econometrica*, *47*, 278.

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *American psychologist*, *39*(4), 341.

Kanter, R. M. (1981). Power, leadership, and participatory management. *Theory into Practice*, *20*(4), 219–224.

Kanter, R. M. (1985). Managing the human side of change. *Management Review*, *74*(4).

Karlsson, R., & Luttropp, C. (2006). Ecodesign: What's happening? an overview of the subject area of ecodesign and of the papers in this special issue. *Journal of Cleaner Production*, *14*(15-16), 1291–1298.

Ketokivi, M., & Choi, T. (2014). Renaissance of case research as a scientific method. *Journal of Operations Management*, *32*(5), 232–240.

Klotz, L., Weber, E., Johnson, E., Shealy, T., Hernandez, M., & Gordon, B. (2018). Beyond rationality in engineering design for sustainability. *Nature Sustainability*, *1*(5), 225–233.

Korteling, J. E., Brouwer, A.-M., & Toet, A. (2018). A neural network framework for cognitive bias. *Frontiers in psychology*, *9*, 1561.

Korteling, J. E., Paradies, G. L., & Sassen-van Meer, J. P. (2023). Cognitive bias and how to improve sustainable decision making. *Frontiers in psychology*, *14*, 1129835.

Kotter, J. P. (1995). Why transformation efforts fail. *Harvard business review*, *73*(2), 59–67.

Laibson, D. (1997). Golden eggs and hyperbolic discounting. *The Quarterly Journal of Economics*, *112*(2), 443–478.

Lavrsen, J., Daalhuizen, J., Dømler, S., & Fisker, K. (2022). Towards a lifecycle of design methods. *Proceedings of DRS2022: Bilbao*. https://doi.org/10.21606/drs.2022.542

Lee, K. (2021). Critique of design thinking in organizations: Strongholds and shortcomings of the making paradigm. *She Ji: The Journal of Design, Economics, and Innovation*, *7*(4), 497–515.

Lewin, K. (1946). Action research and minority problems. *Journal of social issues*, *2*(4), 34–46.

Lewin, K., et al. (1947). Group decision and social change. *Readings in social psychology*, *3*(1), 197–211.

Lindahl, M. (2006). Engineering designers' experience of design for environment methods and tools–requirement definitions from an interview study. *Journal of Cleaner Production*, *14*(5), 487–496.

Lindemann, U. (2002). Flexible adaptation of methods within the design process. *DS 30: Proceedings of DESIGN 2002, the 7th International Design Conference, Dubrovnik*.

Loewenstein, G., & Angner, E. (2003). Predicting and indulging changing preferences. In *Time and decision: Economic and psychological perspectives on intertemporal choice* (pp. 351–391, Vol. 12).

Loewenstein, G., O'Donoghue, T., & Rabin, M. (2003). Projection bias in predicting future utility. *The Quarterly Journal of Economics*, *118*(4), 1209–1248.

Loewenstein, G., & Prelec, D. (1992). Anomalies in intertemporal choice: Evidence and an interpretation. *The Quarterly Journal of Economics*, *107*(2), 573–597.

López-Mesa, B., & Bylund, N. (2011). A study of the use of concept selection methods from inside a company. *Research in Engineering Design*, *22*, 7–27.

Lovallo, D., & Kahneman, D. (2003). Delusions of success: How optimism undermines executives' decisions. *Harvard Business Review*, *81*(7), 56–63.

Luttropp, C., & Lagerstedt, J. (2006). Ecodesign and the ten golden rules: Generic advice for merging environmental aspects into product development. *Journal of Cleaner Production*, *14*(15-16), 1396–1408.

Maffin, D. (1998). Engineering design models: Context, theory and practice. *Journal of Engineering Design*, *9*(4), 315–327.

Mallalieu, A., Hajali, T., Isaksson, O., & Panarotto, M. (2022). The role of digital infrastructure for the industrialisation of design for additive manufacturing. *Proceedings of the Design Society*, *2*, 1401–1410.

Mallalieu, A., Jonasson, A., Petersson, S., Rosendal, M., Hallstedt, S. I., Almefelt, L., & Isaksson, O. (2024). Sustainability criteria for introducing new technologies in low-income contexts. *Proceedings of the Design Society*, *4*, 1359–1368.

Marples, D. L. (1961). The decisions of engineering design. *IRE Transactions on Engineering Management*, (2), 55–71.

Martinsson Bonde, J., Brahma, A., Panarotto, M., Isaksson, O., Wärmefjord, K., Söderberg, R., Kipouros, T., Clarkson, P., Kressin, J., & Andersson, P. (2022a). Assessment of weld manufacturability of alternative jet engine structural components through digital experiments. *ISABE, 2022*.

Martinsson Bonde, J., Isaksson, O., Kipouros, T., Kokkolaras, M., & Andersson, P. (2025). Exploring design trade-offs among sustainability, performance, and manufacturability when considering integration of new technologies. *Proceedings of the Design Society*, *5*, 1635–1644.

Martinsson Bonde, J., Mallalieu, A., Panarotto, M., Isaksson, O., Almefelt, L., & Malmqvist, J. (2022b). Morpheus: The development and evaluation of a software tool for morphological matrices. *DS 118: Proceedings of NordDesign 2022*, 1–10.

Maslow, A. H. (1943). A theory of human motivation. *Psychological review*, *50*(4), 370.

Miles, M. B., Huberman, A. M., & Saldaäna, J. (2014). *Qualitative data analysis: A methods sourcebook*. Sage publications.

Missimer, M., & Connell, T. (2012). Pedagogical approaches and design aspects to enable leadership for sustainable development. *Sustainability: The Journal of Record*, *5*(3), 172–181.

Moore, D. A., & Kim, T. G. (2003). Myopic social prediction and the solo comparison effect. *Journal of Personality and Social Psychology*, *85*(6), 1121–1135.

Moran, J. W., & Brightman, B. K. (2000). Leading organizational change. *Journal of Workplace Learning*, *12*(2), 66–74.

Mutanga, S. S., Simelane, T., & Pophiwa, N. (2013). *Africa in a changing global environment: Perspectives of climate change adaptation and mitigation strategies in africa*. Africa Institute of South Africa.

O'Hare, J., Dekoninck, E., McMahon, C., & Turnbull, A. (2010). Adapting innovation tools to the eco-innovation requirements of industry: Case study results. *International Journal of Design Engineering*, *3*(2), 172–194.

Oreg, S. (2003). Resistance to change: Developing an individual differences measure. *Journal of Applied Psychology*, *88*(4), 680–693.

Oreg, S., Bayazit, M., Vakola, M., Arciniega, L., Armenakis, A., Barkauskiene, R., ... & Van Dam, K. (2008). Dispositional resistance to change: Measurement equivalence and the link to personal values across 17 nations. *Journal of Applied Psychology*, *93*(4), 935–944. https://doi.org/10.1037/0021-9010.93.4.935

Oreg, S., & Sverdlik, N. (2011). Ambivalence toward imposed change: The conflict between dispositional resistance to change and the orientation toward the change agent. *Journal of Applied Psychology*, *96*(2), 337–349.

Oreg, S., Vakola, M., & Armenakis, A. (2011). Change recipients' reactions to organizational change: A 60-year review of quantitative studies. *The Journal of Applied Behavioral Science*, *47*(4), 461–524.

O'Sullivan, O. P. (2015). The neural basis of always looking on the bright side. *Dialogues in Philosophy, Mental and Neuro Sciences*, *8*(1).

Ottosson, S. (2003). Participation action research-: A key to improved knowledge of management. *Technovation*, *23*(2), 87–94.

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H., et al. (1996). *Engineering design: A systematic approach* (Vol. 3). Springer.

Papalambros, P., Gero, J., Maier, A., Cagan, J., Ahmed-Kristensen, S., Albers, A., April, K., Blessing, L., Boujut, J.-F., Cantamessa, M., et al. (2025). Design science: Why, what and how–revisited. *Design Science*, *11*, e48.

Papalambros, P. Y. (2015). Design science: Why, what and how. *Design Science*, *1*, e1.

Park, C. W., & Lessig, V. P. (1981). Familiarity and its impact on consumer decision biases and heuristics. *Journal of Consumer Research*, *8*(2), 223–230.

Parolin, G., Arnbjerg, J., McAloone, T. C., & Pigosso, D. C. (2025). Navigating trade-offs in design for sustainability and circularity: A tool for decision making leveraging narratives and multiple criteria decision analysis. *Journal of Cleaner Production*, *494*, 145004.

Parolin, G., McAloone, T. C., & Pigosso, D. C. (2024). How can technology assessment tools support sustainable innovation? a systematic literature review and synthesis. *Technovation*, *129*, 102881.

Pieroni, M. P., McAloone, T. C., & Pigosso, D. C. (2019). Business model innovation for circular economy and sustainability: A review of approaches. *Journal of Cleaner Production*, *215*, 198–216.

Pigosso, D. C., Rozenfeld, H., & McAloone, T. C. (2013). Ecodesign maturity model: A management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production*, *59*, 160–173.

Potting, J., Hekkert, M. P., Worrell, E., Hanemaaijer, A., et al. (2017). Circular economy: Measuring innovation in the product chain. *Planbureau voor de Leefomgeving*, (2544).

Pugh, S. (1981). Concept selection: A method that works. *Proceedings of the International Conference on Engineering Design*, 497–506.

Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., Choi, J.-K., Kim, H., & Thurston, D. (2010). Integrated sustainable life cycle design: A review.

Redman, A., & Wiek, A. (2021). Competencies for advancing transformations towards sustainability. *Frontiers in Education*, *6*, 785163.

Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy sciences*, *4*(2), 155–169.

Ritzén, S., & Beskow, C. (2001). Actions for integrating environmental aspects into product development. *The Journal of Sustainable Product Design*, *1*(2), 91–102.

Ritzén, S., & Lindahl, M. (2001). Selection and implementation-key activities to successful use of ecodesign tools. *Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 174–179.

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., et al. (2023). Safe and just earth system boundaries. *Nature*, *619*(7968), 102–111.

Ross, L., Greene, D., & House, P. (1977). The false consensus effect: An egocentric bias in social perception and attribution processes. *Journal of Experimental Social Psychology*, *13*(3), 279–301.

Ross, M., & Sicoly, F. (1979). Egocentric biases in availability and attribution. *Journal of Personality and Social Psychology*, *37*(3), 322–336.

Rossi, M., Germani, M., & Zamagni, A. (2016). Review of ecodesign methods and tools. barriers and strategies for an effective implementation in industrial companies. *Journal of Cleaner Production*, *129*, 361–373.

Säfsten, K., & Gustavsson, M. (2020). *Research methodology: For engineers and other problem-solvers*. Studentlitteratur AB.

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological economics*, *119*, 314–325.

Samuelson, W., & Zeckhauser, R. (1988). Status quo bias in decision making. *Journal of Risk and Uncertainty*, *1*, 7–59.

SBTi. (2026). The Science Based Targets - Driving Ambitious Corporate Climate Action. https://sciencebasedtargets.org/

Schkade, D. A., & Kahneman, D. (1998). Does living in california make people happy? a focusing illusion in judgments of life satisfaction. *Psychological Science*, *9*(5), 340–346.

Schöggl, J. P., Baumgartner, R. J., & Hofer, D. (2017). Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. *Journal of Cleaner Production*, *140*, 1602–1617.

Schöggl, J. P., Stumpf, L., & Baumgartner, R. J. (2024). The role of interorganizational collaboration and digital technologies in the implementation of circular economy practices—empirical evidence from manufacturing firms. *Business Strategy and the Environment*, *33*(3), 2225–2249.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. *Knowledge-based systems*, *5*(1), 3–14.

Schulte, J., & Hallstedt, S. I. (2018a). Workshop method for early sustainable product development. *DS 92: Proceedings of the DESIGN 2018 15th International Design Conference*, 2751–2762.

Schulte, J., & Hallstedt, S. I. (2018b). Self-assessment method for sustainability implementation in product innovation. *Sustainability*, *10*(12), 4336.

Schulte, J., Villamil, C., & Hallstedt, S. I. (2020). Strategic sustainability risk management in product development companies: Key aspects and conceptual approach. *Sustainability*, *12*(24), 10531.

Schwartz, M. (1982). Repetition and rated truth value of statements. *The American Journal of Psychology*, 393–407.

Simon, H. A. (1954). Bandwagon and underdog effects and the possibility of election predictions. *Public Opinion Quarterly*, *18*(3), 245–253.

Simon, H. A. (1969). The sciences of the artificial. *The MIT Press.*

Stacey, M., Eckert, C., Pirtle, Z. G., Poznic, M., Schuelke-Leech, B.-A., & Von Der Tann, L. (2025). Methods as a form of engineering knowledge. *Design Science*, *11*, e12.

Statista. (2026). Africa's share in global carbon dioxide (CO2) emissions from 2000 to 2023. Retrieved April 29, 2026, from https://www.statista.com/statistics/1287508/africa-share-in-global-co2-emissions/

Thaler, R. (1980). Toward a positive theory of consumer choice. *Journal of economic behavior & organization*, *1*(1), 39–60.

Thomas, J. C., & Carroll, J. M. (1979). The psychological study of design. *Design studies*, *1*(1), 5–11.

Thomas, R., & Hardy, C. (2011). Reframing resistance to organizational change. *Scandinavian Journal of Management*, *27*(3), 322–331.

Thomke, S., & Fujimoto, T. (2000). The effect of "front-loading" problem-solving on product development performance. *Journal of Product Innovation Management: An International Publication of the Product Development & Management Association*, *17*(2), 128–142.

Trevisan, A. H., Castro, C. G., Gomes, L. D. V., & Mascarenhas, J. (2022). Unlocking the circular ecosystem concept: Evolution, current research, and future directions. *Sustainable Production and Consumption*, *29*, 286–298.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, *185*(4157), 1124–1131.

Tversky, A., & Kahneman, D. (1981). The framing of decisions and the psychology of choice. *Science*, *211*(4481), 453–458.

Ullman, D. G. (1992). *The mechanical design process* (Vol. 2). McGraw-Hill New York.

Ulrich, K. T., & Eppinger, S. D. (2016). *Product design and development*. McGraw-hill.

United Nations. (2022). The Sustainable Development Goals Report 2022. Retrieved April 8, 2024, from https://unstats.un.org/sdgs/report/2022/

United Nations. (2026a). Sustainable Development Goal 12: Ensure sustainable consumption and production patterns. https://www.un.org/sustainabledevelopment/sustainable-consumption-production/

United Nations. (2026b). The Sustainable Development Goals. https://www.un.org/sustainabledevelopment/

Van Boven, L., Dunning, D., & Loewenstein, G. (2000). Egocentric empathy gaps between owners and buyers: Misperceptions of the endowment effect. *Journal of Personality and Social Psychology*, *79*(1), 66–76.

Van Boven, L., & Loewenstein, G. (2003). Social projection of transient drive states. *Personality and Social Psychology Bulletin*, *29*(9), 1159–1168. https://doi.org/10.1177/0146167203254600

Van de Ven, A. H., & Sun, K. (2011). Breakdowns in implementing models of organization change. *Academy of Management Perspectives*, *25*(3), 58–74.

Vicente, J., & Camocho, D. (2024). Design for sustainability tools: Definition and criteria towards practical use. *Journal of Cleaner Production*, *479*, 144041.

Villamil, C., & Hallstedt, S. (2021). Sustainabilty integration in product portfolio for sustainable development: Findings from the industry. *Business Strategy and the Environment*, *30*(1), 388–403.

Villamil, C., Nylander, J., Hallstedt, S. I., Schulte, J., Watz, M., et al. (2018). Additive manufacturing from a strategic sustainability perspective. *DS 92: Proceedings of the design 2018 15th international design conference*, 1381–1392.

Vilochani, S., Borgianni, Y., McAloone, T. C., & Pigosso, D. C. (2024). An investigation into the extent to which sustainable product development practices are implemented in manufacturing companies. *Sustainable Production and Consumption*, *50*, 155–167.

Vinnova. (2020a). Demonstration of infrastructure for digitalization enabling industrialization of additive manufacturing (didam). https://www.vinnova.se/en/p/digital-sustainability-implementation-package---dsip/

Vinnova. (2020b). Digital sustainability implementation package (dsip). https://www.vinnova.se/en/p/digital-sustainability-implementation-package---dsip/

Vinnova. (2022). Designing the impact of digital product passport (dipp). https://www.vinnova.se/en/p/designing-the-impact-of-digital-product-passport--dipp/

Vinnova. (2023). Circular and data driven collaborative design framework (cadcod). https://www.vinnova.se/en/p/circular-and-data-driven-collaborative-design-framework-cadcod/

Vinnova. (2024a). Cirkularitet - FFI - våren 2024. Retrieved April 8, 2024, from https://www.vinnova.se/e/utlysning-2022-00048/cirkularitet-ffi-varen-2024/

Vinnova. (2024b). Sustainable materials data ecosystem. https://www.vinnova.se/en/p/-sustainable-materials-data-ecosystem/

Walker, D., & Myrick, F. (2006). Grounded theory: An exploration of process and procedure. *Qualitative health research*, *16*(4), 547–559.

Wallace, K. (2011). Transferring design methods into practice. In *The future of design methodology* (pp. 239–248). Springer.

Watz, M. (2020). Using group model building to foster learning for strategic sustainable development. *Sustainability*, *12*(20), 8350.

Watz, M., & Hallstedt, S. I. (2020). Profile model for management of sustainability integration in engineering design requirements. *Journal of Cleaner Production*, *247*, 119155.

Watz, M., & Hallstedt, S. I. (2022). Towards sustainable product development–insights from testing and evaluating a profile model for management of sustainability integration into design requirements. *Journal of Cleaner Production*, *346*, 131000.

Watz, M., & Hallstedt, S. I. (2024). Depth and detail or quick and easy? benefits and drawbacks of two approaches to define sustainability criteria in product development. In *Ecodesign for sustainable products, services and social systems i* (pp. 413–427). Springer.

Weber, E. U. (2017). Breaking cognitive barriers to a sustainable future. *Nature Human Behaviour*, *1*(1), 0013.

Weinstein, N. D. (1980). Unrealistic optimism about future life events. *Journal of Personality and Social Psychology*, *39*(5), 806–820. https://doi.org/10.1037/0022-3514.39.5.806

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability science*, *6*, 203–218.

Willem, R. A. (1990). Design and science. *Design Studies*, *11*(1), 43–47.

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th international conference on evaluation and assessment in software engineering*, 1–10.

Woofter, J., Schulte, J., & Sandgren Watz, M. (2026). Ai-assisted leading sustainability criteria development: A multiple case study. *Proceedings of the Design Society*.

World Economic Forum. (2023). Reducing the carbon footprint of the manufacturing industry through data sharing. Retrieved April 8, 2024, from https://www.weforum.org/impact/carbon-footprint-manufacturing-industry/

Zwicky, F. (1967). The morphological approach to discovery, invention, research and construction. *New methods of thought and procedure: contributions to the symposium on methodologies*, 273–297.

Appendix I - Guide & template: Industrial adoption approach

Instructions and guiding material for the *needs-driven and collaboration-based approach* that facilitates the industrial adoption of new design methods

This document outlines and explains a *needs-driven and collaboration-based approach*. It consists of six overarching steps, generic templates, and guiding questions. The purpose of the approach is to guide and support researchers, managers, and design teams in identifying, selecting, adapting, and adopting new design methods that align with their current design setting and needs. The approach is highly iterative and requires close involvement among key stakeholders to develop a deep and shared understanding of the company, its context, and the *situational design problems* that require attention. Examples of relevant stakeholders to include in the adoption process, based on the eight case studies, are:

- *Method experts*, since they have competence and experience in the design method, i.e., the ability to modify and adapt the design method appropriately based on the input acquired during the adoption process
- Designers or design teams[1], since they will be the ones using the design method in their daily operations
- Sustainability experts, and/or sustainability governance, since they are aware of current issues related to environmental impact or inequalities in the value chain, can provide more accurate data, and since many of the efforts related to integrating sustainability into the design process are linked to different legislations and directives
- Managers, or project leaders, should preferably be involved in some of the steps, since it is important to achieve buy-in and both obtain and accommodate potential resource constraints
- Engineering specialists, since many of the design methods focused on sustainability, adopt a systemic perspective and often require multidisciplinary teams, which may require involvement of e.g., specialists/representatives from supply chain and manufacturing operations
- Representatives from 'process, method, and tools development functions', since they have a good understanding of the overall internal processes and tools used internally, and thus how a new design method could fit into this ecosystem, while also complying with the design logic and terminology

The approach includes six generic steps, illustrated and briefly described in Figure 1. Steps 1-3 focus on supporting the *method expert* in understanding the designers' context, together with the involved stakeholders, and in capturing this visually so it can be communicated and understood by all involved stakeholders. Step 4 focuses on understanding the problems the designers face (i.e., *situational design problems*, *situational sub-problems*, and *contextual problems*). An in-depth, shared understanding of such problems serves as a basis for understanding the needs and for recognizing that current design practices are insufficient to deliver more sustainable solutions. This is important to capture explicitly and mutually agree upon to frame the need for new design methods focused on sustainability. Step 5 focuses on identifying and selecting candidate design methods from the toolbox that have the potential to support addressing the identified design method needs[2]. Step 6 focuses on adapting the selected design methods using a 'trial-and-error' approach based on the outcomes from Steps 1-5, so they can be appropriately adopted.

[1] Many modern organizations outsource several design tasks and instead use *product*- or *component owners* for some parts or components, and it is appropriate to involve them in such cases.

[2] This process can, without doubt, identify design method needs' that are difficult to meet with the existing and available design methods, and thus require further research.

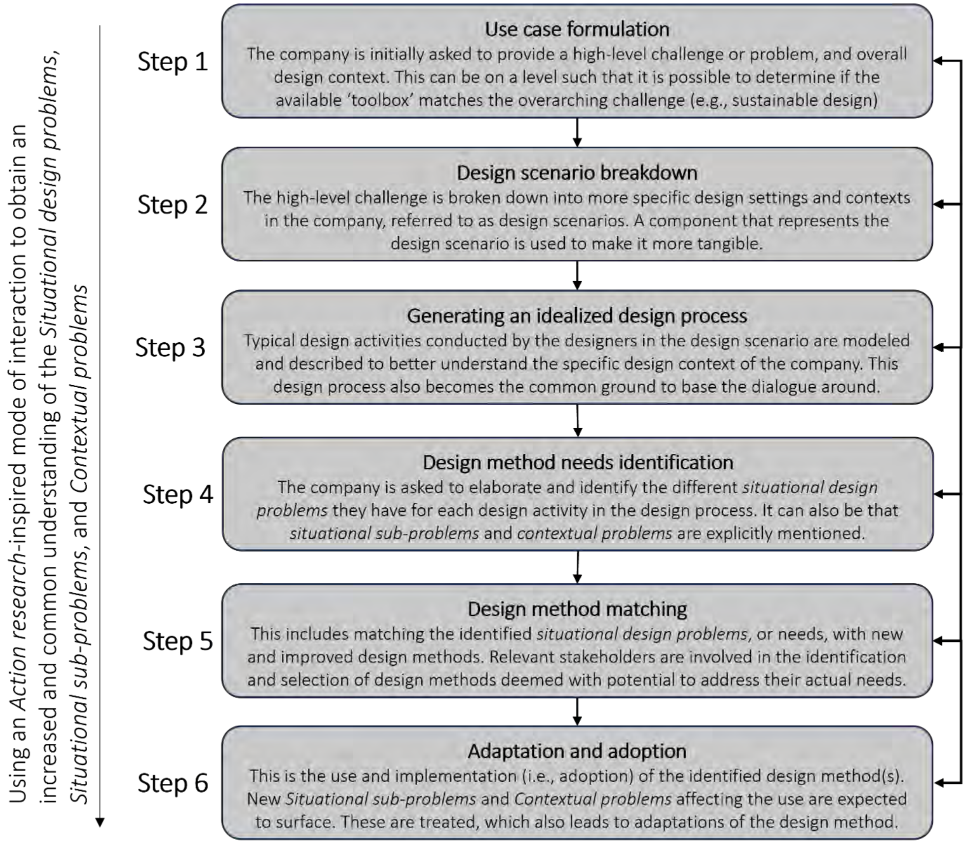


Figure 1. *The collaborative design method adoption approach*. It consists of six generic steps and uses an action research-inspired approach to engage internal stakeholders.

The needs-driven and collaboration-based approach, by design, supports the *method expert* and the designer/design team in identifying, selecting, and adapting new design methods to meet their needs. First, use a *design process logic* as a tool, or means of communication, since *design processes* are effective in structuring, governing, and facilitating the fuzzy activity of *designing*. Second, in line with *action research*, relevant actors are heavily involved throughout the adoption process, raising awareness and providing valuable input to foster a sense of ownership and autonomy, which are critical for internal motivation and social acceptance of the proposed design methods. Combined, these two elements ensure key contextual aspects are considered by actively prompting the emergence of *situational design problems* and *contextual problems*, allowing them to be addressed appropriately during the adoption process. In turn, ensuring that the new design methods align with the current design context and the design team's needs. All six steps are presented in more detail in the subsections below, along with empirical results from case study A1, to highlight how outcomes from using the approach can appear in practice.

Step 1 – Use case formulation

The purpose of Step 1 (*use case formulation*) is to ensure that all actors are actively involved in problem scoping and agree that the available toolbox aligns with the overarching challenge. The generic template for capturing Step 1 outcomes is shown in Figure 2.

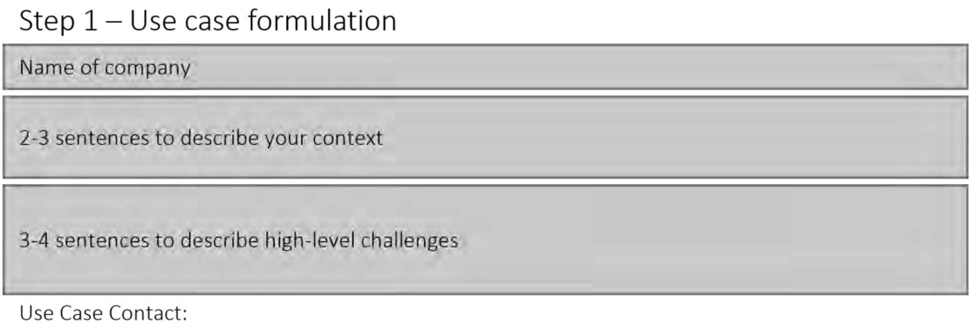


Figure 2. *Generic template for Step 1 – Use case formulation*.

The practical goal of Step 1 is to, via close involvement and facilitated dialogue, understand and formulate the high-level challenge and overall design context, i.e., where in the organization and roughly how the design methods are intended to support practitioners. For example:

- *What are the overarching challenges in the organizational context?* It must be clear what the high-level challenge is related to, for example, *design for additive manufacturing*, *sustainability*, *user-centered design*, *robust design*, or other overarching design topics
- *Where in the organizational structure and overarching product development process are these design settings typically occurring?* Is it, for example, *the early phases of the design process*, or *the later stages?*
- *Who is typically involved during these stages in the design process?* Is it in the intersection between, e.g., *product planning*, *R&D*, or *manufacturing & operations?*

Step 1 is complete when the *use case formulation* is sufficient and has saturated, allowing determination of whether the available toolbox is a good fit and has the potential to address the overarching challenges. This step can be done either top-down, to identify which design teams need to be brought into the design method adoption process, or bottom-up, with a design team, and later generalized to apply across several design teams in the organization. In essence, the *use case formulation* should be generic enough to apply to multiple design teams, yet specific enough to determine whether the available design method(s) can support the *situational design problems* designers and design teams face. Moreover, this step also clarifies what internal resources (i.e., functions and personnel) need to be engaged in the design method adoption process. The empirical result from case study A1 is presented in Figure 3, illustrating how an outcome can arise in Step 1.

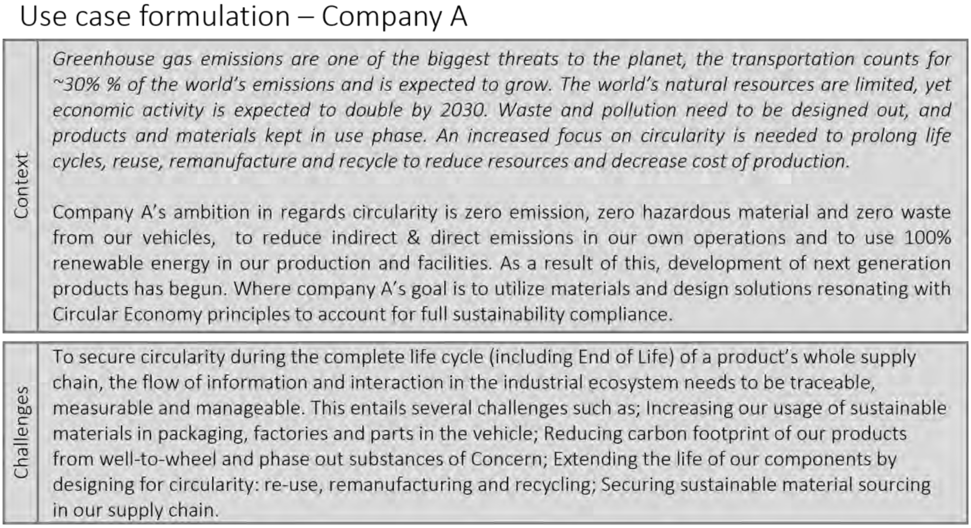


Figure 3. *Results from Step 1 for case study A1*.

Step 2 – Design scenario breakdown

The purpose of Step 2 (*design scenario breakdown*) is to involve relevant actors to create a sense of ownership, but also to ensure that the captured design scenario resonates with the actual design setting of the designers, while also using representative labels and terms people recognize. This is also why designers must be brought in during Step 2, at the latest. The generic template for capturing Step 2 outcomes is shown in Figure 4.

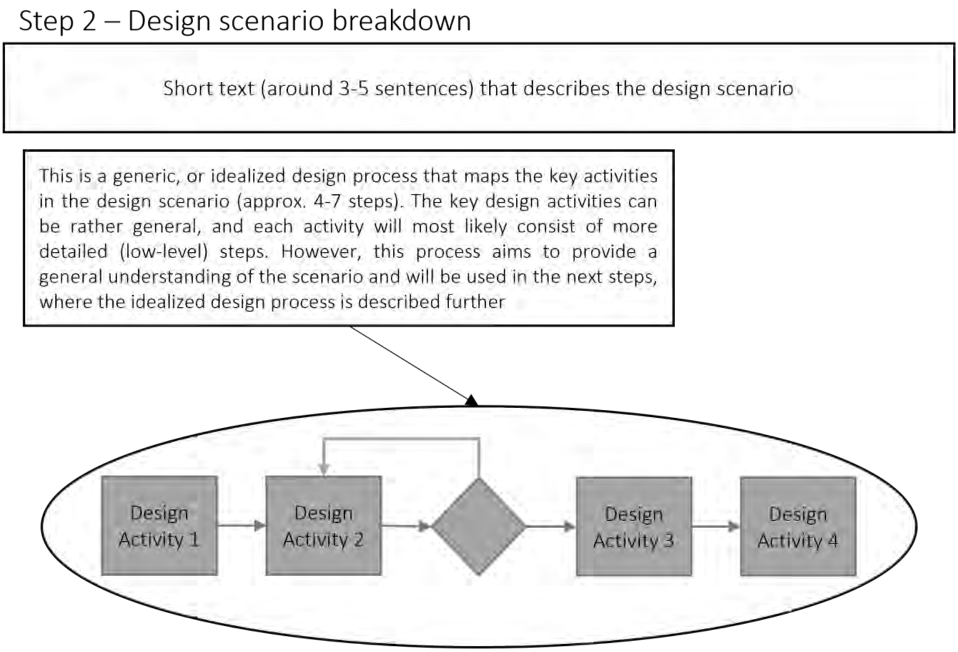


Figure 4. *Generic template for Step 2 – Design scenario breakdown.*

The practical goal of Step 2 is to, via close involvement and dialogue, more narrowly and concretely specify a *design scenario* within this use case, i.e., a specific design setting in the overall design context. Involving a case component, product, or technology is typically beneficial for this step, as the design scenario needs to be more concrete and precise than the use case formulation. Furthermore, deeper involvement of the actual designers or design teams is necessary at this step, since the design scenario should reflect the specific, unique design process of each designer or design team, which may vary across design teams within an organization. As previously mentioned, this involvement is either initiated in Step 1 or Step 1 provides input on what design teams should be involved in Step 2. Similar questions from Step 1 are relevant to Step 2, but those involving a specific component and design team should stimulate new, more concrete questions and answers for that specific design scenario. Moreover, it is typically difficult to describe the current design scenario by words alone. This dialogue is therefore facilitated by visual mapping of common design activities elicited from the design team, which also stimulates the *design scenario breakdown*. Examples include:

- *Where in the organizational structure and overarching product development process is this design scenario situated?*
- *What is a representative and relevant component or part for this design scenario (that also aligns with the use case formulation)?* It is also useful to ask for a rough description (including an illustration) of the component or part
- *What are common design activities carried out in the design of this component or part?* E.g., defining requirements, preliminary material selection, geometrical design, simulation, testing, concept gate, or other
- *Who or what functions are typically involved in this design scenario, and what expertise is required?*
- *What and where are decisions about the design made in this design scenario?* This could be preliminary and soft decisions, but also more formal decisions in different product gates or releases
- *Are there any dependencies among or iterations between these design activities?* E.g., is the generated information or knowledge linked to downstream design activities or decisions, or are there hidden iterations between different design activities
- *What are the common and overarching challenges or problems you face in this design scenario, both in and between the different design activities?* Problems here can relate to, e.g., a lack of time or communication among involved stakeholders

Step 2 is complete when a representative and relevant component or part has been selected, and the overarching and common design activities used in the design process for that component have been identified and captured visually. It should also be clear which functions are expected to be involved, and that this *design scenario* aligns with and appropriately represents the *use case formulation*. It is also worth acknowledging that the combined set of activities typically and theoretically follows a similar design logic, i.e., a progression of loops including a mix of analysis, synthesis, and evaluation leading to a final design, despite contextual differences such as exact sequencing, source of data, or terminology, which are treated in more detail in Step 3. Figure 5 shows an example outcome from Step 2 retrieved from case study A1.

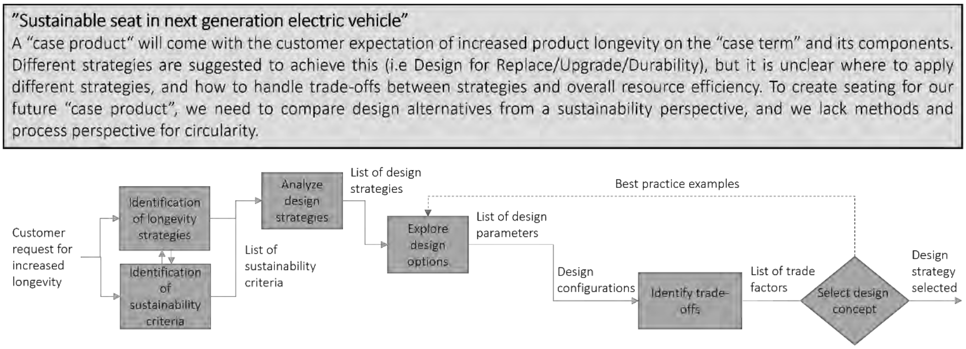


Figure 5. *Results from Step 2 for case study A1*. Sensitive terms have been generalized to maintain confidentiality.

Step 3 – Generating an idealized design process

The purpose of Step 3 (*generating an idealized design process*) is to explicitly frame and capture the design process, creating common ground and a shared understanding among the stakeholders involved in the adoption process, which can also be used for communication. As stated in Step 2, it is also important that the actual design scenario be appropriately framed using internal terminology and concepts, i.e., aligned with company language. Furthermore, internal charts and descriptive documents can serve as valuable input for better understanding and capturing the formal processes and activities within the case company. Altogether, the dialogue in Step 3 causes more contextual problems as the discussions become more concrete and specific to the actual design scenario. In turn, this makes it easier to adapt the design method at a later stage (Step 6) and to foster a greater sense of ownership by creating a feeling of 'our design method'. Figure 6 highlights the template and icons used to model the *idealized design process* in Step 3.

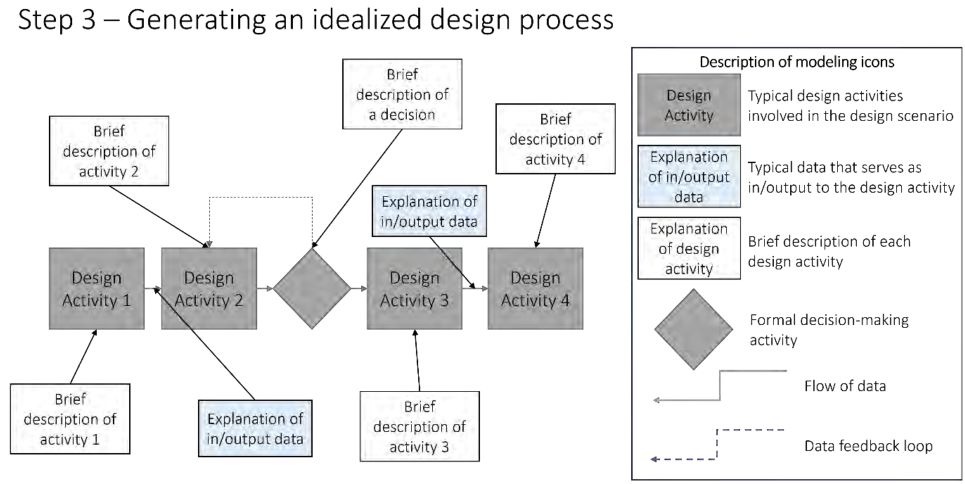


Figure 6. *Generic template for Step 3 – Generating an idealized design process.*

Step 3 builds on the *design scenario breakdown,* and the practical goal is to, via close involvement and dialogue, obtain a more detailed description of each of the specified design activities framed as an *idealized design process*. This step may also require more detailed input and involvement from other stakeholders in the *design scenario*, e.g., material experts for preliminary material selection or simulation engineers. Furthermore, each design activity in the process needs to be described, along with the activity's common and intended outputs. The description should clarify:

- *What is typically happening in this design activity*?
- *Who is typically involved in this design activity*?
- *What is the typical time spent on these design activities and in between?*
- *What is the purpose of the design activity?*
- *What is the desired outcome from the design activity*? E.g., what type of information or knowledge
- *What other design methods or tools are currently used in this design activity*?
- *What knowledge, information, or data is typically available, and where does it come from?* E.g., are different databases used, does the knowledge come from another design method, testing, or simulation
- *Are there feedback loops? Is the outcome of some activity used elsewhere,* or *downstream in the design process?*
- *Where, and based on what or how, is this the basis for design decisions, both formal and informal?* Being more specific about the design activities makes it easier to identify more dependencies among these
- *What are the common problems or issues occurring in this design activity?* Preferably, this question is discussed more narrowly concerning the focus of the available design methods, i.e., sustainable design for the case studies used as examples in this guide

Step 3 is complete when an idealized design process that frames the *design scenario* has been visually captured. Typically, the greater the detail and fidelity of the idealized design process, the better. However, it becomes a trade-off between the time spent on this detailed dialogue and visual capturing. Moreover, the *idealized design process* needs to be clear and comprehensible so it can be used to communicate with other stakeholders involved in adopting the design method. In essence, the *idealized design process* should be detailed enough for the *method expert* to understand where a candidate design method would be used and its potential limitations (e.g., access to information and data, synergies with other design methods or tools, specialist competence, and time). This is also why this step is referred to as "*generating an idealized design process*"; it is not the exact design process, but as close as possible. The empirical result from case study A1 is presented in Figure 7 to illustrate how an outcome can arise in Step 3.

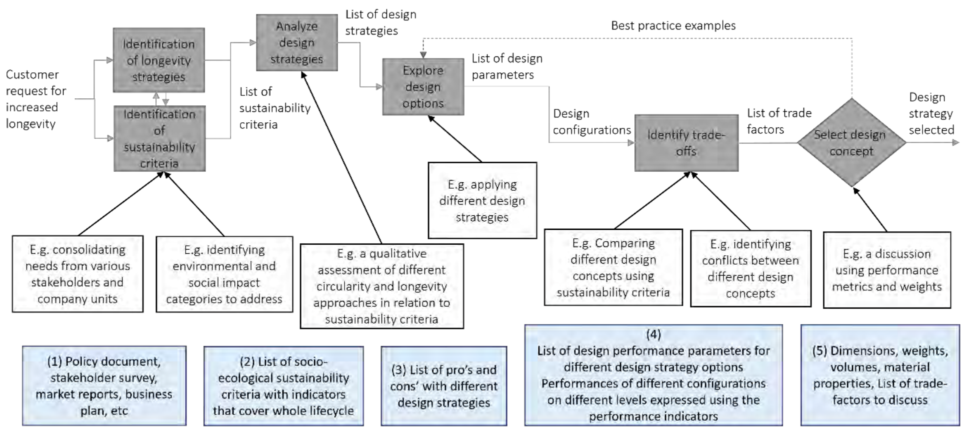


Figure 7. *Empirical results from Step 3 for case study A1.*

Step 4 – Design method needs identification

The purpose of Step 4 (*design method needs identification*) is to involve relevant actors to foster a sense of ownership and raise awareness of key issues in their design process. And, to ensure that the identified problems/needs/concerns are streamlined, saturated, and mature. In turn, this enables the proposal of candidate design methods to address these key issues. Figure 8 illustrates the template used to capture these problems/needs/concerns, highlighting that different ways of phrasing and framing these problems are encouraged.

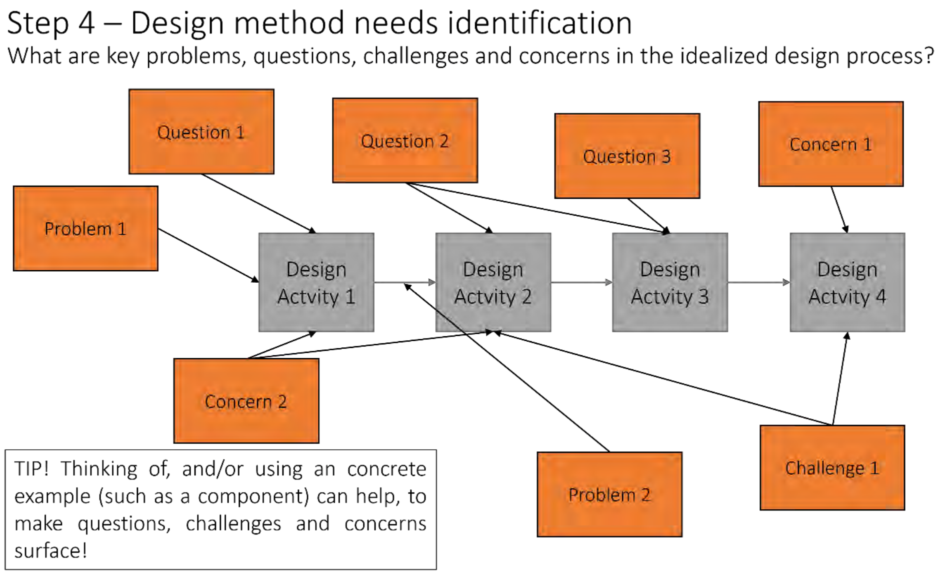


Figure 8. *Generic template for Step 4 – Design method needs identification.*

The practical goal of Step 4 is to elicit and formulate, through close involvement and dialogue, the needs, problems, or challenges that designers, design teams, or other stakeholders experience or perceive during their design process. Again, we refer to these as *situational design problems* because they are 'problems' that designers face in their specific, or situational, context and are captured through dialogue with relevant stakeholders. Furthermore, the problems raised can also relate to aspects of the design activities, such as their inputs and outputs (e.g., data quality) and variations in how information is phrased. In turn, the problems raised can thus also relate to *contextual problems*. Such problems are an important input to Step 6, which focuses on adapting the design method to the designers' context. Problems have, in most cases, already been raised in the previous steps, but the focus here is to explicitly capture the problems, for example:

- *How to do [insert problems/needs/concerns]?*
- *We need the ability to do [insert problems/needs/concerns]?*
- *In what way can we do [insert problems/needs/concerns] better?*

Although practitioners are generally good at raising issues they experience, it is still beneficial if the method expert also uses probing techniques to ensure relevant issues are raised during this process. For example, through questions such as:

- *Have you thought of this?*
- *How do you consider, manage, or comply with this today?*

- *Can you elaborate a bit regarding this?*

Furthermore, many available design methods typically treat generic, recurring *situational design problems* applicable across different *design scenarios* and *use cases*. In turn, the *method expert* can support this ideation step by nudging designers or design teams with common situational design problems others have previously encountered, i.e., common design method needs. In turn, this support raises new perspectives that stakeholders may also find helpful, as sustainable design is a relatively immature field within manufacturing companies.

Representative examples of how practitioners explicitly phrased such problems/needs/concerns in the case studies are presented in Table 2 below.

Table 2. Examples of problems/needs/concerns were explicitly phrased by practitioners.

Examples of problems/needs/concerns raised by practitioners	**Company**
"Difficult to compare alternative materials, where suppliers provide 'sustainability' arguments, often using LCAs, but we as integrators need to include the longevity aspects of the vehicle."	A
"What criteria are relevant and how are they used to characterize and evaluate sustainability performance?"	A
"How do we measure the progress to become more circular?"	D
"There is no established way of evaluating plastic material from a sustainable perspective. How do we evaluate virgin plastic (w.r.t., e.g., component compounds, etc)? Recycled plastics are preferred, but difficult to evaluate plastics in general."	B
"How do we ensure that the grounds behind the decisions can be traced?"	D
"Are there trade-offs possible for what would be the right level, should it be re-purpose rather than re-manufactured. Re-furbished etc"	A
"We lack knowledge/understanding about how different strategies affect/impact on system levels"	A
"How do we ensure that the requirements are maintained on a level that is transferable to concept development and that they are maintained?"	A
"How to make sound sustainability decisions early in the design phase (before LCA can be made)"	A
"How do we ensure that everybody is involved in the process (to become sustainable)?"	D
"How can we generate more sustainable concepts with limited data/ knowledge/ information on what is more sustainable?"	C
"It would be beneficial to have an 'app' where one can grade how sustainable a suggested material is, preferably transparent with other partners/suppliers."	B
"We need a tool to guide designers/engineers to select the right plastic materials. 'Company B' must also propose a way to categorize recycled plastics and provide a tool for Tier 1 suppliers to evaluate sustainable plastics."	B
"It is usually possible to get people to come to workshops, it's a half-day, otherwise managers say no – people are occupied in a project already"	B
"There are several tools, and not really clear where information can be found or collected."	A
"Need new tools to compare materials, before we only chose based on cost – we cannot do that anymore"	A
"I am a squared engineer sometimes, what speed (of the vehicle) are we defining for? We need figures."	A
"The lead time/resource to make decisions during design is severely constrained, so any design method needs to comply with the design team conditions existing, also with the production volume targeted."	B

The phrasing of the elicited problems or needs typically requires refinement; some can be screened out, while others might evolve throughout the process. It is also possible to weigh/prioritize the importance of the problems raised by stakeholders, if deemed necessary.

Furthermore, limitations related to use and implementation become more evident during Step 4 (e.g., time and available resources), and explicit requests for contextual adaptations of the design methods (i.e., *contextual problems*) are made. Common examples include:

- The desire to link the design methods to internal information and data management systems, and other existing design methods & computerized tools
- Adjustments and simplifications, i.e., reducing the scope of the design methods, use of internal resources and personnel, and the dedicated time to use the design methods
- Improvements and modifications to the interface of the design methods such that they are more user-friendly, intuitive, can be used more efficiently, and are adapted to the company language.

This is considered natural as the problem framing becomes more precise and concrete. Furthermore, it is important to separate *situational design problems* from contextual problems to match them with candidate design methods in Step 5. However, the *contextual problems* remain relevant to acknowledge, capture, and consider, as they are useful inputs to Step 6. This categorization can thus both simplify and support the adaptation of the design method, as well as support the exclusion of candidate design methods that would be a poor fit. Step 4 is completed when the problems raised have saturated, enabling identification and selection of suitable design methods in Step 5.

The matured, i.e., screened, refined, evolved, and saturated results from case study A1 are presented in Figure 9 to highlight how an outcome can be illustrated in Step 4.

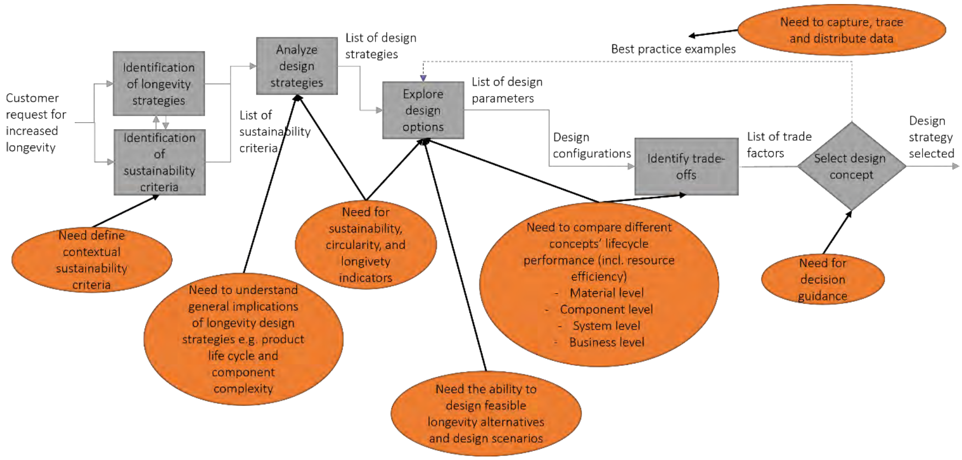


Figure 9. *Empirical results from Step 4 for case study A1.*

Here, they are phrased consistently as "need to" to emphasize the needs-driven focus of the approach, and all should relate to what we classify as *situational design problems*. This, in turn, enabled us to match the "needs" with specific design methods available in the toolbox. The *method expert* should support this iterative process, as he or she is knowledgeable about the design methods and can help streamline the articulated needs, so they align with the scope and terminology of the available design methods.

Moreover, it needs to be emphasized that Step 4 is an ideating exercise where a variety of problems can (and need to) be identified, and the process of eliciting these problems/needs/concerns is highly iterative. Table 2 highlights that many of the raised problems are coarse and contain a mix of *situational design problems*, *situational sub-problems*, and *contextual problems*. Some problems may also go beyond the scope of available design methods, underscoring the need to develop new methods (e.g., through *design research*).

Step 5 – Design method matching

The purpose of Step 5 (*design method matching*) is to involve relevant stakeholders in decision-making and in assessing which design methods serve as candidate alternatives. In turn, this creates a sense of ownership and increasing transparency regarding the design methods- applicability, expected outcomes, and potential limitations. Moreover, because some design methods can require significant adaptation, it is also important to be transparent about how that adaptation can influence outcomes. In general, it is important that relevant stakeholders are involved in the design method matching to ensure agreement on which design methods are feasible candidates. In practice, this procedure can be captured and visualized using the output from Step 4, with numbers or other indicators representing different design methods placed on the identified *situational design problems* or design method needs.

The practical goal of Step 5 is to, through close involvement and dialogue, identify and select candidate design methods that can potentially address the design method needs identified in Step 4, i.e., situational design problems. The design method matching also needs to consider the raised *situational sub-problems* and *contextual problems* since these will influence the applicability of the candidate design methods. For example:

- *What information and data are available*? And if information and data are lacking, *can we make appropriate assumptions instead?*
- *Do we have the required competencies?* (e.g., material or manufacturing technology experts)
- *Can the scope of the design method be adjusted or reduced without significant implications for the outcome?*
- *Can the design method be used in conjunction with existing design methods and computerized tools?*

In turn, it is also important that each design method in the toolbox includes information that conveys, e.g., when, how, and why it is relevant.[3] This can, for example, be accessible through a *method expert*, or via a digital repository.

The empirical result from case study A1 is presented in Figure 10, illustrating how an outcome can arise in Step 5. The green circles represent candidate SPD design methods, and the blue circles represent candidate SED design methods. For context, more than 20 design methods were available for selection.

[3] Gericke, K., Eckert, C., & Stacey, M. (2022). "Elements of a design method–a basis for describing and evaluating design methods" in *Design Science*, proposes what information and guidance any design method should be acquainted with for understanding its appropriate use and implementation.

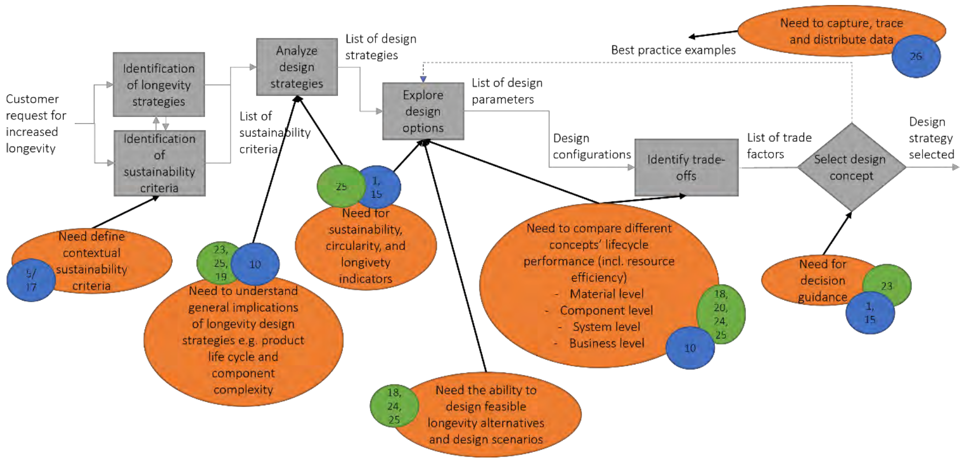


Figure 10. *Empirical results from Step 5 for case study A1.* The numbers in the blue circles represent candidate design methods from the SPD category, and the numbers in the green circles represent candidate design methods from the SED category.

Step 5 can serve as a learning process for stakeholders involved, helping them understand their own design-method needs or *situational design problems*. It can lead to the realization that a *situational design problem* is worth solving, i.e., the knowledge about the design problem it supports in generating is highly relevant. But the organization lacks the necessary infrastructure or capabilities to adopt the design method effectively, and internal efforts are needed to enable adoption. Excessive adaptations can significantly affect the outcome and validity of the design method. For example, if too many rough assumptions are needed due to insufficient information and data. It is, therefore, in such situations more appropriate for the organization to change, i.e., adapt, to accommodate the design method, rather than for the design method to change. This can relate to:

- Recruitment of new personnel with new and relevant competencies
- Internal competence development efforts, e.g., lifecycle thinking, circular design
- The collection of new types of necessary information and data from, e.g., suppliers, or testing
- Or other necessary changes in the current design process or organizational structure that, e.g., limit cross-functional collaboration

Step 6 – Adaptation and adoption

The purpose of Step 6 (*adaptation and adoption*) is to foster a 'trial-and-error' mindset among stakeholders and to create a sense of ownership. Hence, the close involvement of relevant stakeholders in this step is crucial, as they can influence and feel included in decisions related to the adaptation and intended use of the proposed new design methods.

The practical goal of Step 6 is to, through close involvement and a 'trial-and-error approach', adapt the selected design methods so they can be appropriately adopted, i.e., adapted to fit the needs and context of the designers or design teams, without significantly influencing the intended outcomes. An iterative approach is recommended, as necessary adaptations may only become apparent when designers or design teams 'get their hands dirty' by interacting with the design methods, i.e., using and testing them. Additionally, the case studies made it clear that there is no 'one-size-fits-all' for adapting the design methods, as the *contextual problems* raised by stakeholders vary significantly and thus require different measures (or solutions) to be appropriately addressed. It should also be noted that this 'trial-and-error' approach can push us back to previous steps. For example, if initial testing and use of a design method indicate that it inadequately addresses the identified issues or requires extensive adaptations.

Three representative examples are provided to provide further clarification:

- In study B1, during the use and implementation of one design method, it became evident that the terminology used in one of the design methods, which focuses on trade-off analysis, differed from the company's terminology. Company B used the term *design objectives* instead of the term *design criteria*, which was used in this design method. This turned out to be non-problematic, as these terms were deemed to share a similar purpose in the company's internal design logic. However, anticipating this before testing the design method was challenging and could have significant consequences if they differed, e.g., if *design criteria* are treated as 'loose' objectives and *design objectives* as 'fixed' objectives.
- The specific and individual lifecycle phases of the case products differed for all companies, and the design methods had to be adapted accordingly when used and implemented to fit the company language and product logic.
- Sustainability is systemic, and the practitioners commonly requested to reduce the scope, which in practice was done by varying how many and what sustainability criteria to include in the analyses carried out. Furthermore, this adaptation largely depends on the specific company and the product in question.

The adaptation activity is thus non-straightforward and typically requires experience and competence, i.e., expertise in both the design method and in sustainability for sustainability-focused methods. Step 6 is therefore preferably carried out with the support of the method expert and supplementary material that guide the designer and/or design team during use and implementation, which will be elaborated upon in Section 5. Moreover, it is essential to emphasize that it is challenging to anticipate all necessary adaptations in practice before a new design method has been thoroughly tested.

Additional remarks

The adoption of a new design method will require some changes to designers' current practices, and they need to be open to them. In some instances, it may be more appropriate to adopt a new design method incrementally, i.e., by implementing single facets over time. Such an approach can enable the organization to evolve strategically and improve toward more sustainable design practices over time, e.g., by making changes aligned with the subsequent introduction of new regulations. Finally, a designer or design team with deep knowledge of their own context, priorities, and ongoing operational work is arguably best equipped to determine when and how some facets of the design method can be integrated into their current design practices, to some extent. Nevertheless, involving them in the adoption process will increase the likelihood that they are open to such changes, as this approach (by design) aims to foster a sense of ownership, promote work autonomy, and increase awareness of key sustainability issues in their design process.

The role of a facilitator

This approach is dependent on three distinct sets of competencies and skills

First, the approach requires an individual with sufficient competence and experience in using and applying the available design methods, so that they can be appropriately modified and adapted. There is, otherwise, a risk of causing excessive harm to their methodological procedures and, thus, to the intended outcomes. It is also beneficial if this individual is aware of the consequences of different modifications and can effectively communicate their effects on outcomes to the stakeholders involved. This is what has been referred to as a *method expert* throughout this document. Additionally, this individual should possess experience and competence in *designerly ways of knowing, thinking, and acting*, enabling them to effectively understand and contextualize within the manufacturing company's internal terminology and design logic. This type of competence and skill has been elaborated upon before within the context of *design*. This individual can be an external and an internal resource.

Second, the approach also requires an individual with leadership qualities who can manage and drive the change, since adopting a new design method will entail some change to current design practices. In some instances, it can be appropriate for the adoption of a new design method to be incremental, i.e., single facets are implemented over time, since this allows the organization to evolve and improve strategically, e.g., making changes in line with the subsequent introduction of new regulations. As mentioned, a designer or design team with deep knowledge of their own context, priorities, and ongoing operational work is arguably best equipped to determine when and how facets of the design method can be integrated into their current design practices. The approach, therefore, does not prescribe how change should occur, but promotes flexibility and focuses on stakeholder involvement in the adoption process, allowing people to influence the change. In turn, this will increase the likelihood that they are open to the required changes, as the approach (by design) aims to foster a sense of ownership, promote work autonomy, and increase awareness of key sustainability issues in their design process. Furthermore, criticism and resistance to change can occasionally stem from concerned employees who see flaws in the proposed change, and this input can be used to improve it. The skills or competence to manage such issues is occasionally referred to as a *change agent*.

Third, individuals who drive and manage 'sustainability change' initiatives within organizations are sometimes referred to as *sustainability change agents* and require a new set of competencies and skills, such as normative, systems-thinking, and interpersonal skills. There are new types of obstacles that *sustainability change agents* need to face in manufacturing companies. For example, sustainability initiatives are not necessarily driven by short-term profit but may relate to more ambiguous long-term business success factors, such as resource scarcity, and thus influence employees' sense of urgency. Many key targets and explicit sustainability ambitions within manufacturing companies also extend far into the future, such as 2040 net-zero targets and the transition to more circular product offerings. Sustainability is also systemic, requiring a lifecycle perspective that employees typically perceive as complex, difficult to manage, and at odds with the organizational structures of many manufacturing companies. Moreover, being isolated, having vague strategic targets, and lacking a clear role in decision-making are common problems.

The combined skills and competencies highlighted above are currently treated in the literature as three distinct sets of skills, or roles, i.e., *method expert*, *change agent*, and *sustainability change agent*, and are not easily taught or acquired. It is unclear if these capabilities can be possessed by a single individual in manufacturing organizations.

Appendix II - Template: Interactive assessment method

Sustainability Information and Data Management Capability Assessment Method

Background and rationale:
The ability to exploit the potential sustainability performance of a new sustainable material can be limited/constrained by the current information and data management capabilities, i.e., the ability to manage sustainability information and data effectively and efficiently. In such cases, strategic actions should be taken to ensure the full sustainability potential of the new sustainable material can be exploited. It is important to understand that the information and data capabilities of an ecosystem, or single actor, are not an end, but a means to drive sustainability performance, e.g., improving traceability at EoL to enable recirculation of the material, or driving accountability via reporting directives.

Instructions:
Step 1. Revisit and read upon the product critiera, desired sustainability information and data, and provided/existing sustainability information and data.
Step 2. Assess each key criteria with respect to this. Also, add a qualitative assessment to provide more nuance to the assigned grade.
Step 3. Go through sub-steps a-c to highlight what hotspots that need further attention, and propose strategies and actions

Intended use and purpose:
The assessment should be made in the early phases of design and can be used by individual designers/engineers, and internal and/or external multidisciplinary teams in workshop settings (involving, e.g., designers, PLM experts, procurement, suppliers, and others). The assessment can be done in iterations throughout the design process as the solution and ecosystem evolve. The purpose is to, as early as possible, understand how the existing sustainability information and data can either support or limit the development of more sustainable solutions. More specifically, by:

i) Highlighting the current maturity and ability to provide sustainable information and data in the collaborative ecosystem
ii) Streamlining requirements and expectations on sustainable information and data management capabilities in the sustainable material data ecosystem
iii) Identifying hotspots and proposing strategic actions to address the key issues

Product/component:

Step 2						Step 3		
Assessment criteria	**Low performance (1-3)**	**Medium performance (4-6)**	**High performance (7-9)**	**Grade between 1-9, and add a qualitative assessment**	**Sustainable material data hotspot** E.g., if there is any particular data that is considered critical to address, or of interest, or should be removed.	**a) What are the implications and potential consequences of this?** E.g., increased cost, reduced sustainability performance, affects our ability to realize the solution, or to meet reporting legislations.	**b) How does it affect us, and is this an implication we need to address?** E.g., do the potential consequences have a negative or significant impact, or are the consequences uncertain and instead pose a risk.	**c) What strategic actions should be taken to address this?** E.g., develop or utilize existing standards, develop or implement software, streamline data formats, invest in internal competence, or change the design.
1. Actuality	*Sustainability information and data in the ecosystem are not up to date*	*Critical sustainability information and data in the ecosystem are up to date*	*Relevant sustainability information and data in the ecosystem are up do date*	*E.g., Data are continuously checked and updated (<10 days), or collected using sensors with real-time data, or data are not considered subject to large fluctuations.*				
2. Accuracy	*Sustainability information and data in the ecosystem are inaccurate*	*Critical sustainability information and data in the ecostem are accurate*	*Relevant sustainability information and data in the ecosystem are accurate*	*E.g., data correspond to the real value, or use precise quantitative values, or collected via standard.*				
3. Reliability	*Sustainability information and data in the ecosystem are not reliable*	*Critical sustainability information and data in the ecosystem are reliable*	*Relevant sustainability information and data in the ecosystem are reliable*	*E.g., validated using neutral/third-party actors, or testing, or provided by a trusted partner.*				
4. Accessability	*Sustainability information and data in the ecosystem are not accessible*	*Critical sustainability information and data in the ecosystem are accessible*	*Relevant sustainability information and data in the ecosystem are accessible*	*E.g., data can efficiently be retrieved by relevant stakeholders using a smart digital system*				
5. Completeness	*Sustainability information and data in the ecosystem are not complete*	*Critical sustainability information and data in the ecosystem are complete*	*Relevant sustainability information and data in the ecosystem are complete*	*E.g., data covers the full impact across the full lifecycle, such as cradle-to-grave, or uses appropriate unit/measure to represent real impact*				
6. Scalability	*Sustainability information and data in the ecosystem are not scalable*	*Critical sustainability information and data in the ecosystem are complete*	*Relevant sustainability information and data in the ecosystem are scaleable*	*E.g., classifications, structures, or formats are not unique and can be used outside of this application, or standards are utilized*				
7. Flow security	*Sustainability information and data flows in the ecosystem are not secure*	*Critical sustainability information and data flows in the ecosystem are secure*	*Relevant sustainability information and data flows in the ecosystem are secure*	*E.g., utilize a software/digital system that ensures no risk of leaks, changes, or compromise of data, or contractual agreements*				
8. Storage security	*Sustainability information and data storage in the ecosystem are not secure*	*Critical sustainability information and data storage in the ecosystem are secure*	*Relevant sustainability information and data storage in the ecosystem are secure*	*E.g., utilize a software/digital system that ensures no risk of leaks, changes, or compromise of data, or contractual agreements*				
9. Communicability	*Sustainability information and data in the ecosystem are not communicable*	*Critical sustainability information and data in the ecosystem are communicable*	*Relevant sustainability information and data in the ecosystem are communicable*	*E.g., data are understood by relevant stakeholders (end users, downstream actors, product designers, others) using standards, or intuitive representations and definitions*				
10. Transparancy	*Sustainability information and data in the ecosystem are not transparent*	*Critical sustainability information and data in the ecosystem are transparent*	*Relevant sustainability information and data in the ecosystem are transparent*	*E.g., relevant data are not disclosed or confidential despite sensitivity*				
11. Traceability	*Sustainability information and data in the ecosystem are not traceable*	*Critical sustainability information and data in the ecosystem are traceable*	*Relevant sustainability information and data in the ecosystem are traceable*	*E.g., the origin and evolution of data are accessible to relevant stakeholders*				
12. Ownership	*Sustainability information and data in the ecosystem have no ownership*	*Critical sustainability information and data in the ecosystem have ownership*	*Relevant sustainability information and data in the ecosystem have ownership*	*E.g., roles and responsibilities associated with data are clear, such as who ensures data is up to date*				
13. Value of I&D	*Sustainability information and data in the ecosystem have no value*	*Critical sustainability information and data in the ecosystem have value*	*Relevant sustainability information and data in the ecosystem have value*	*E.g., data provides value to stakeholders, such as support improving sustainability performance, or legislative requirements*				
14. Labor intensity	*Management of sustainability information and data in the ecosystem are labor-inefficient*	*Management of critical sustainability information and data in the ecosystem are labor-efficient*	*Management of relevant sustainability information and data in the ecosystem are labor-efficient*	*E.g., time and resources required to manage data (e.g., consolidation, reporting, ensuring up-to-date and accurate, or storage) is considered reasonable and fair among stakeholders.*				

Appendix III- Empirical data from applying the industrial adoption approach

Empirical results from applying the needs-driven and collaboration-based approach to eight industrial case studies

The empirical results from all eight case studies are presented below, all of which have sustainable design scopes. Some steps lack an outcome because certain elements were introduced and refined throughout development.

Case study A1 – The sustainable and circular design of a seat in the new generation of electric vehicles

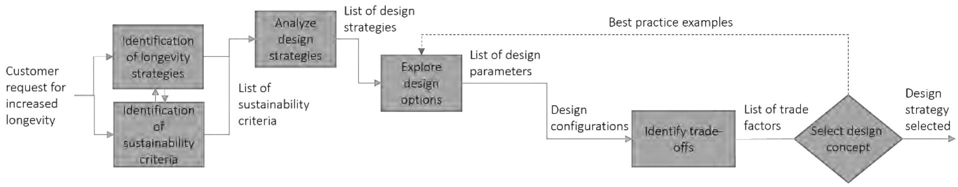
Outcome from Step 1

Use case formulation – Company A

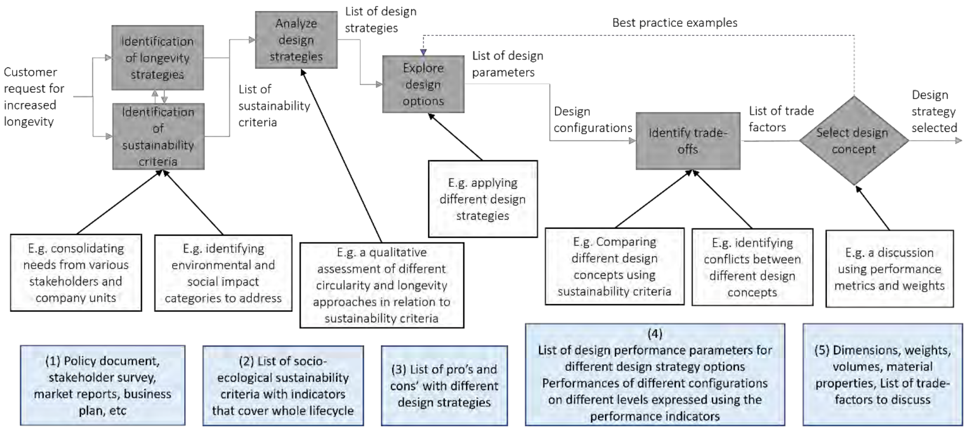
Context	*Greenhouse gas emissions are one of the biggest threats to the planet, the transportation counts for ~30% % of the world's emissions and is expected to grow. The world's natural resources are limited, yet economic activity is expected to double by 2030. Waste and pollution need to be designed out, and products and materials kept in use phase. An increased focus on circularity is needed to prolong life cycles, reuse, remanufacture and recycle to reduce resources and decrease cost of production.* Company A's ambition in regards circularity is zero emission, zero hazardous material and zero waste from our vehicles, to reduce indirect & direct emissions in our own operations and to use 100% renewable energy in our production and facilities. As a result of this, development of next generation products has begun. Where company A's goal is to utilize materials and design solutions resonating with Circular Economy principles to account for full sustainability compliance.
Challenges	To secure circularity during the complete life cycle (including End of Life) of a product's whole supply chain, the flow of information and interaction in the industrial ecosystem needs to be traceable, measurable and manageable. This entails several challenges such as; Increasing our usage of sustainable materials in packaging, factories and parts in the vehicle; Reducing carbon footprint of our products from well-to-wheel and phase out substances of Concern; Extending the life of our components by designing for circularity: re-use, remanufacturing and recycling; Securing sustainable material sourcing in our supply chain.

Outcome from Step 2

"Sustainable seat in next generation electric vehicle"
A "case product" will come with the customer expectation of increased product longevity on the "case term" and its components. Different strategies are suggested to achieve this (i.e Design for Replace/Upgrade/Durability), but it is unclear where to apply different strategies, and how to handle trade-offs between strategies and overall resource efficiency. To create seating for our future "case product", we need to compare design alternatives from a sustainability perspective, and we lack methods and process perspective for circularity.



Outcome from Step 3



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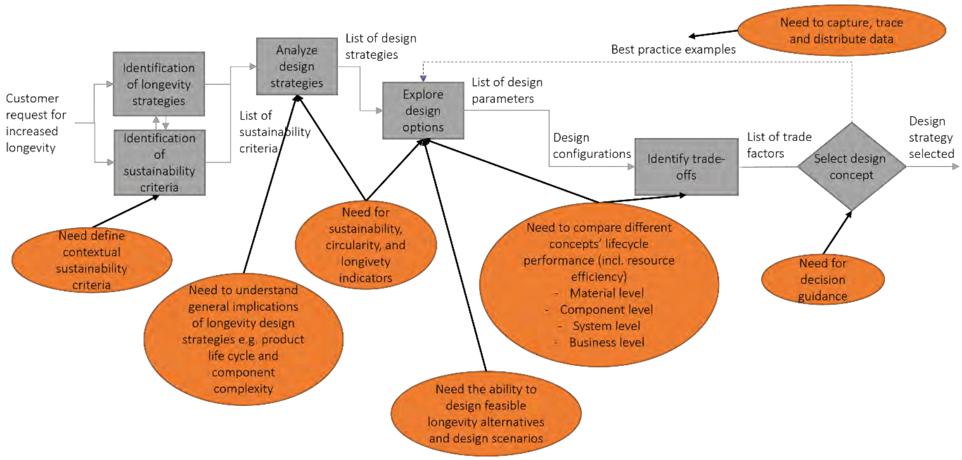
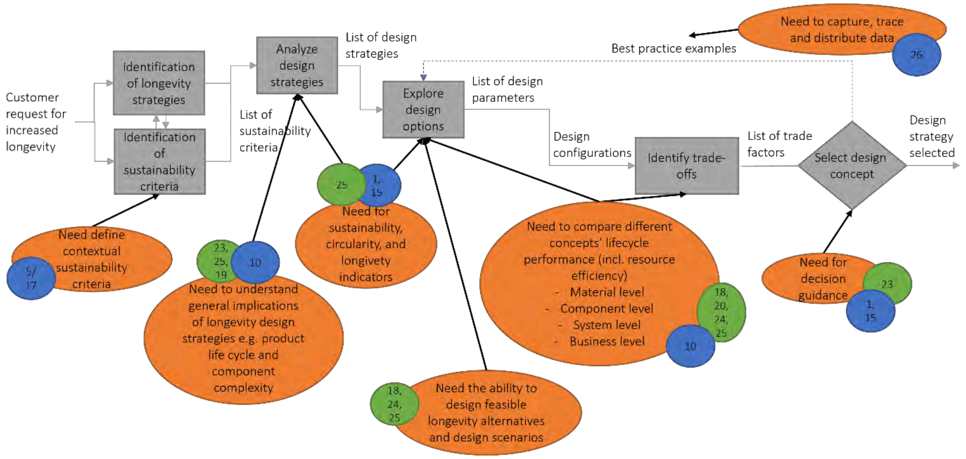


Outcome from Step 5

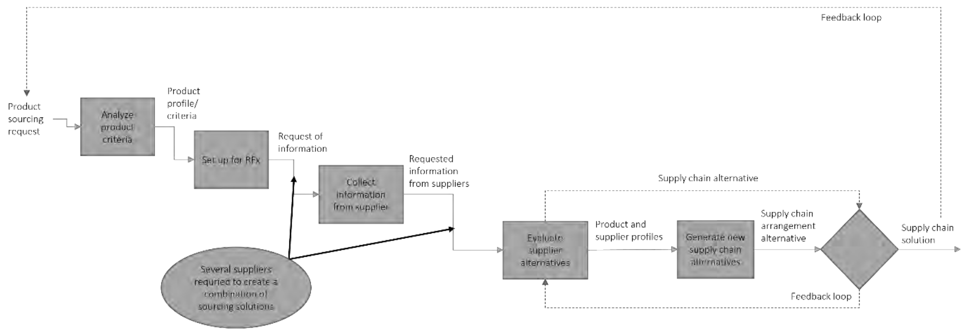


Case study A2 – Sustainable and circular supply chains for a seat in the new generation of electric vehicles

Outcome from Step 1 is the same as for case study A1

Outcome from Step 2

"Collaboration processes and tools in Circular supply chains"
To secure circularity during the complete life cycle (incl. EoL) of a product's whole supply chain, the flow of information and interaction in the industrial ecosystem needs to be traceable, measurable and manageable.
- Which circular criteria to be used, measuring circularity, traceability, maturity levels, financial flows in circular models, parts warranty, etc.
- Requirement specifications for circularity, RFx processes and tools to handle multiple parties, contracts in a multiple parties' environment, etc



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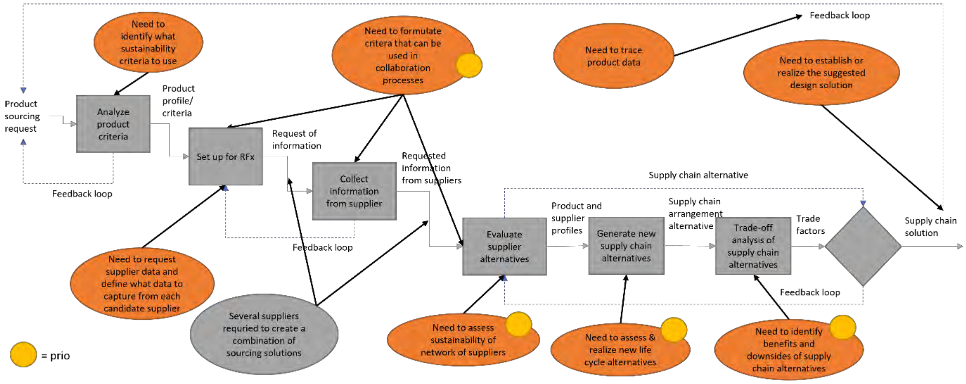
Outcome from Step 4



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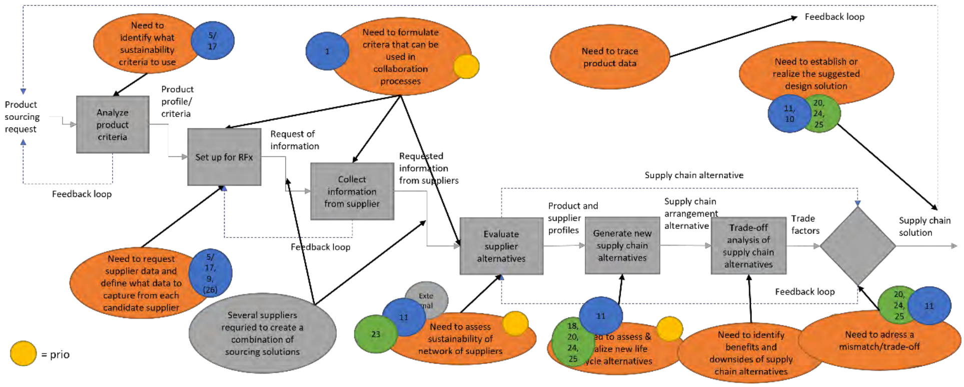


Case study B1 – Sustainable material selection for a cable bracket component

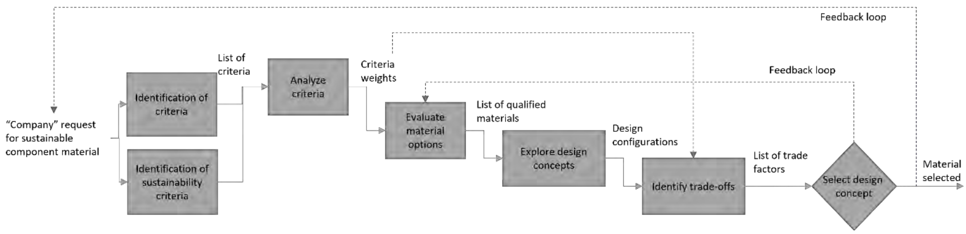
Outcome from Step 1

Use case formulation – Company B

Context	"Company" wants to secure a more sustainable way to use plastic components in our products. Plastics could be made from virgin or bio-based or re-used plastics, it's a question of trade-offs between quality, price & sustainability.
Challenges	How to chose polymer material based on sustainability performance? There is no established way of evaluating plastic material from a sustainable perspective. How do we evaluate virgin plastics? (e.g component compunds) Re-cycled plastics are preferred, but difficult to evaluate plastics in general. UN2030 targets are desired to relate to/meet sustainability vs cost perspective. At present, the lack of competence, leads to over specified designs, or conservative (re-used plastic) solution. The lead time/resource to make decisions during design is severely constrained why any design method need to comply with the design team conditions existing – also with the production volume targeted. We need a tool to guide designers/engineers to select the right green materials.

Outcome from Step 2

"Sustainable plastic components"
"Company B" wants to secure a more sustainable way to use plastic components in our products. Plastic parts could be made from fossil oil, bio-based polymers or re-used plastics, it's a question of trade-offs between quality, price & sustainability. There is today no established way to evaluate, categorize and quality assure plastic material from a sustainable perspective. We need a tool to guide designers/engineers to select the right plastic materials.



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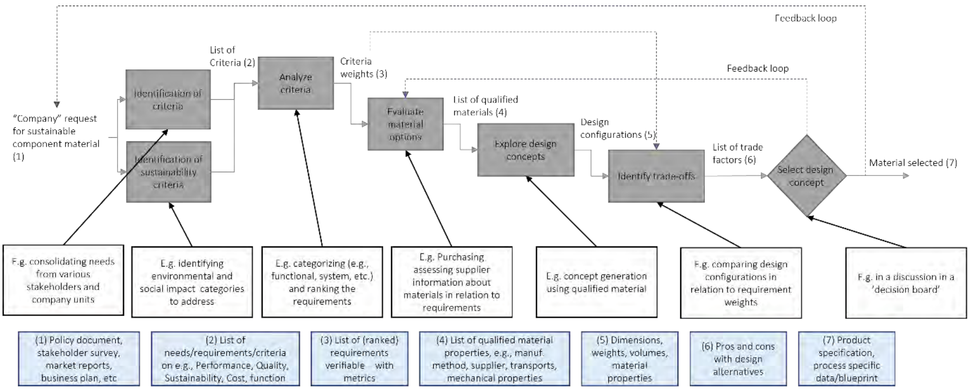

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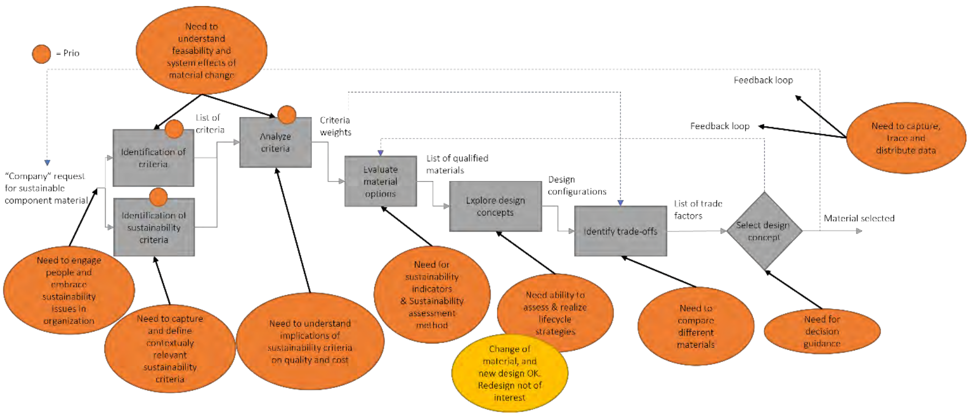

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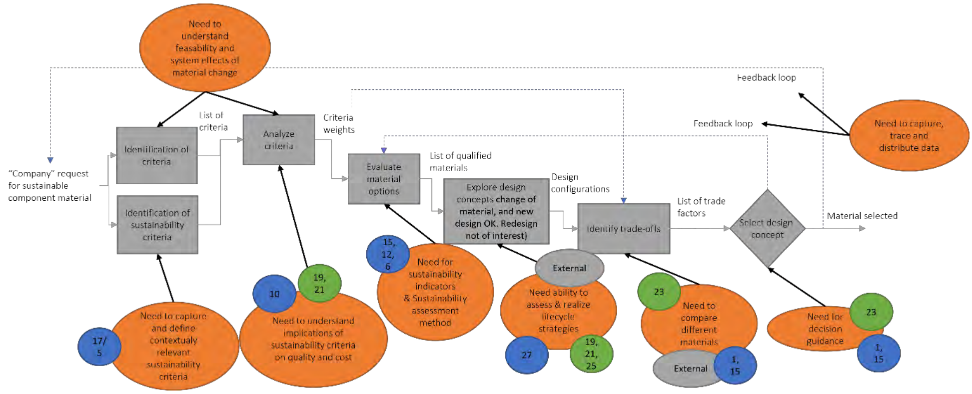


Case study C1 – Sustainable design of a turbine rear structure using laser powder bed fusion

Outcome from Step 1

Use case formulation – Company C

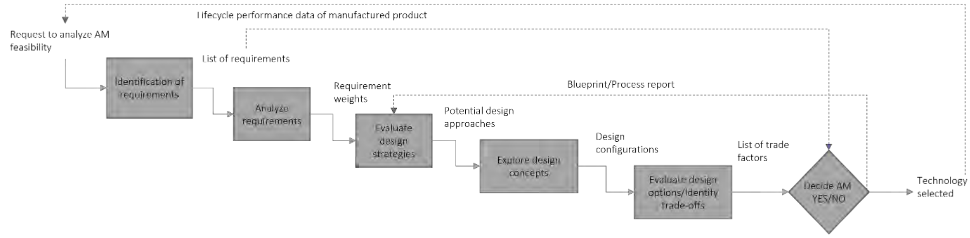
Context	Company C as a business will achieve net zero greenhouse gas emissions by 2050. We will design products that enable our customers to manufacture "products" that emit net zero greenhouse gas emissions throughout their life-cycle by 2050. We will minimise our impact on the environment, conserving natural resources and eradicating hazardous waste. Company C explores different ways of using additive manufacturing (AM): • Design of new products • Repair of products AM technologies: • Laser Powder Bed Fusion (LPBF): can be used to create more light weight designs, reduce lead time, increase value add, involve new suppliers and add functions to the product. • Laser metal deposition (LMD): can be used to lower waste, decrease cost, add functionality, extend life and repair products. Our aim is to learn more about the sustainability impact of these technologies and their different design parameters. We need to explore the sustainability perspective of these technologies (circularity, data gathering/handling, sustainable decision-making during design, evaluation compared to traditional manufacturing processes)
Challenges	How we take circularity and sustainability into account during concept selection and design of a new product? How can we generate sustainable concepts with limited data/ knowledge/ information on what is more sustainble? How do we handle trade offs? How can we optimize AM for sustainability? How do we know when repairing a product is more sustainable than replacement of a new product? How do we estimate and visualize the value of repair? How do we know whether the (repaired) component is as airworthy as a new product? How do we use repair data in the design of new products?

Outcome from Step 2

”Design for sustainability with AM”

Laser Powder Bed Fusion (LPBF) can be used to create more light weight designs, reduce lead time, increase value add, involve new suppliers and add functions to the product. Laser metal deposition (LMD) can be used to lower waste, decrease cost, add functionality, extend life and repair products. Need to explore the sustainability perspective of these technologies (circularity, data gathering/handling, sustainable decision-making during design, evaluation compared to traditional manufacturing processes).

- Company C develops “product” and investigates the use of Additive Manufacturing(AM) specifically Laser PowderBed Fusion (LPBF) for decreased lead time and increased material quality.
- At present the sustainability impact of LPBF suffer from lack of data during design phases. Seeking ways to gather and create necessary data, enabling designers to do value based/informed tradeoffs between LPBF and other techniques.



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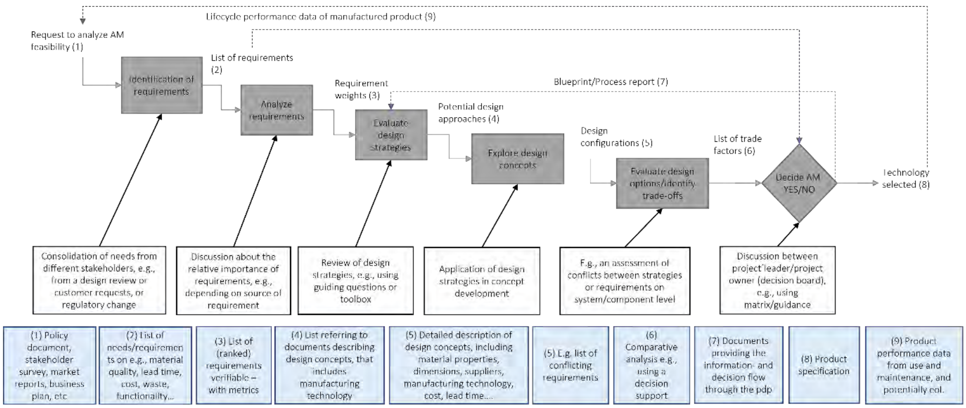

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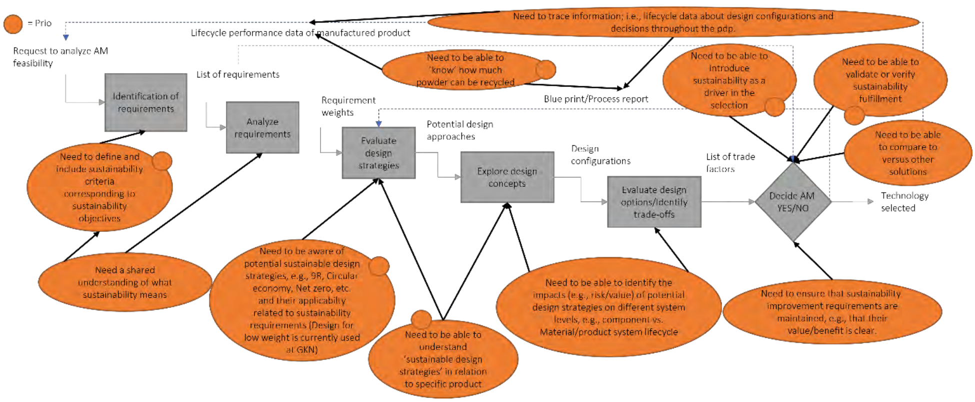

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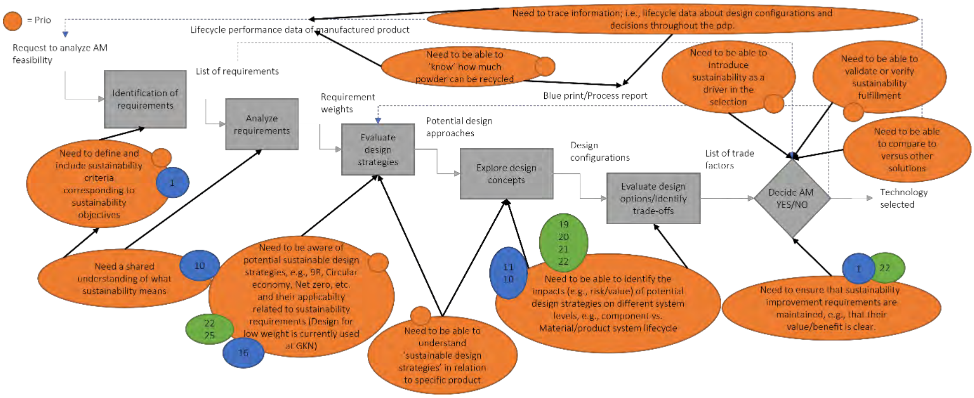
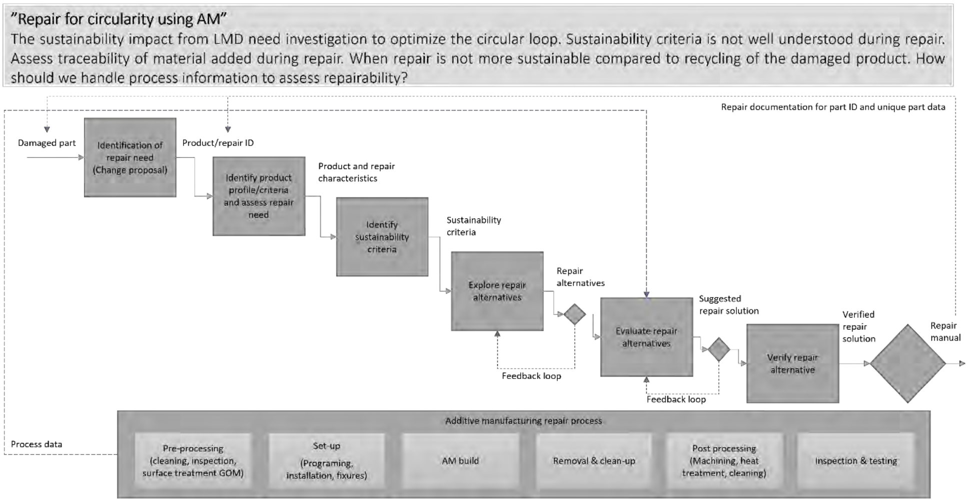


Case study C2 – Sustainable repair of a fan blade with direct energy deposition

Outcome from Step 1 is the same as for case study C1

Outcome from Step 2



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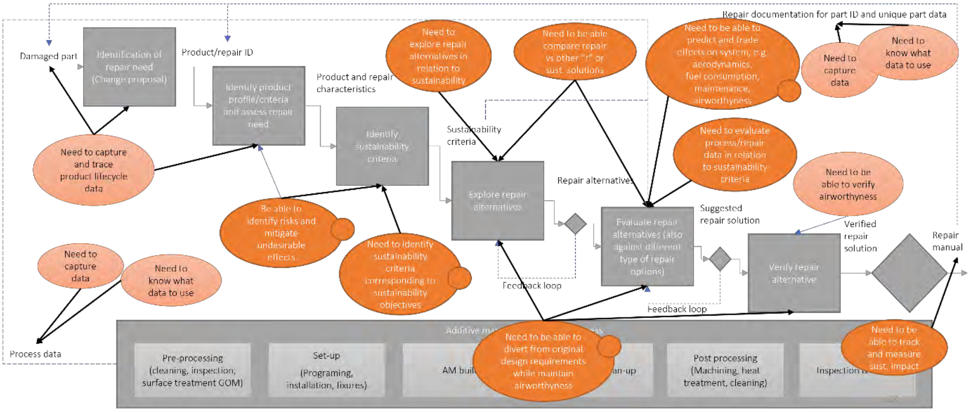

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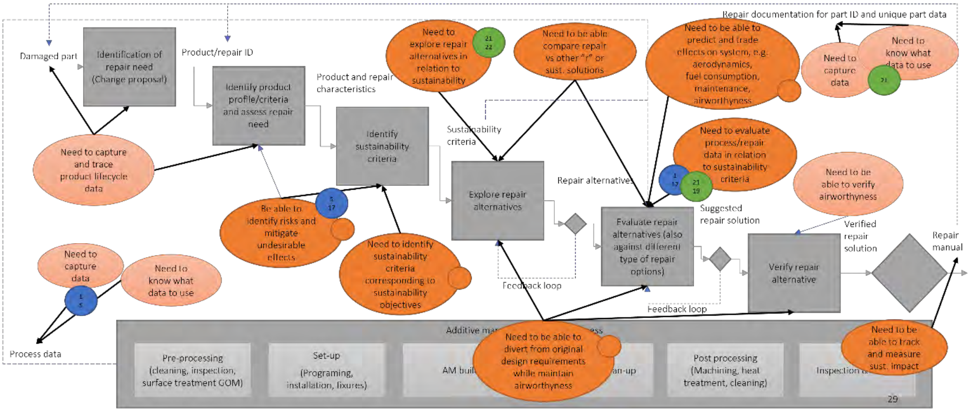


Case study D1 – Strategically integrating sustainability in global product management

Outcome from Step 1

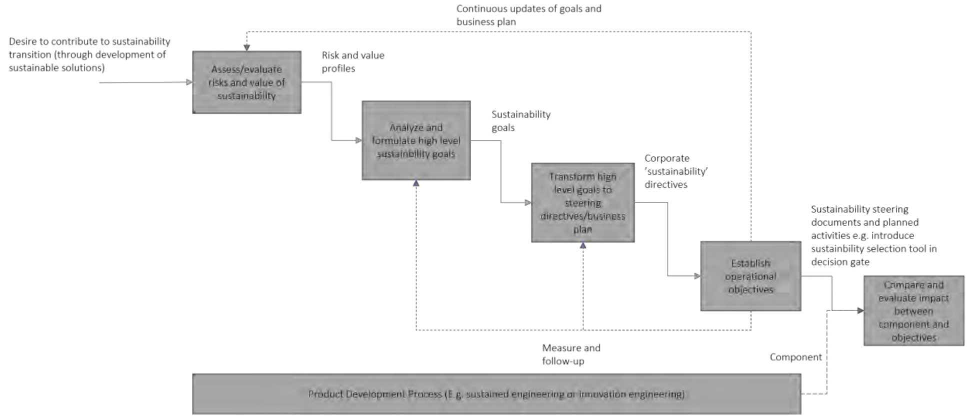
Use case formulation – Company D

– Designing sustainable cable & pipe sealing solutions

Context:	Company A3 is starting a journey towards sustainability for the entire business with its focus on being the leading provider of cable & pipe sealing solutions through employment of sustainable principles.
Challenge:	Our current business model effectively provides solutions for any cable & pipe sealing situations but is based on linear resource flows. We do not have sufficient means to support our designing and production of solutions with circular resource flows that contributes to sustainability. There is a need to explore alternative, and preferably circular, business scenarios and to drive the development of our products in a sustainable way. This involves identifying and evaluating sustainability aspects with regards to e.g., risks, requirements, suppliers, materials and lifecycle monitoring and management. Then our decision-makers can consider sustainability performance in relation to customer expectations and value, enabling tradeoffs. It is expected that the results can be used to enhance our knowledge and skills to design for sustainability, including education of staff, as well as de-risking our ideas and initiatives.

Outcome from Step 2

"Sustainability governance"
Company D currently lacks the global steering and management decision support needed to meet its own sustainability goals. Today´s improvement work is limited and not systematic enough. Concrete steering that enables proactive decisions, which may support the extensive design changes is needed.



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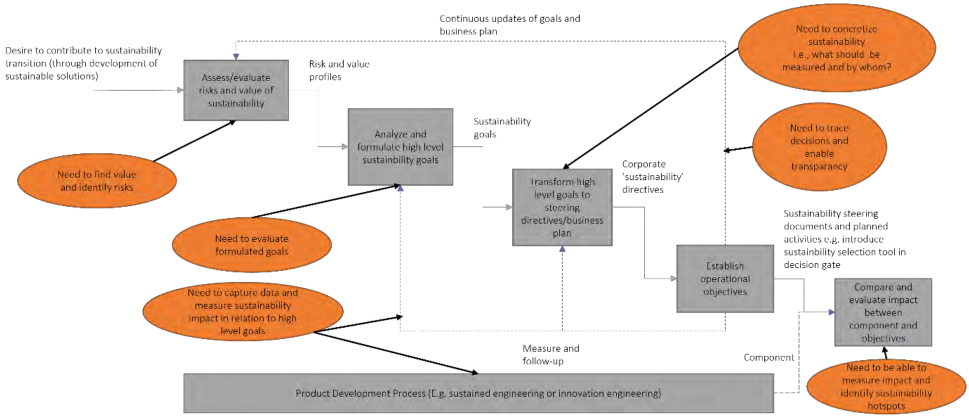

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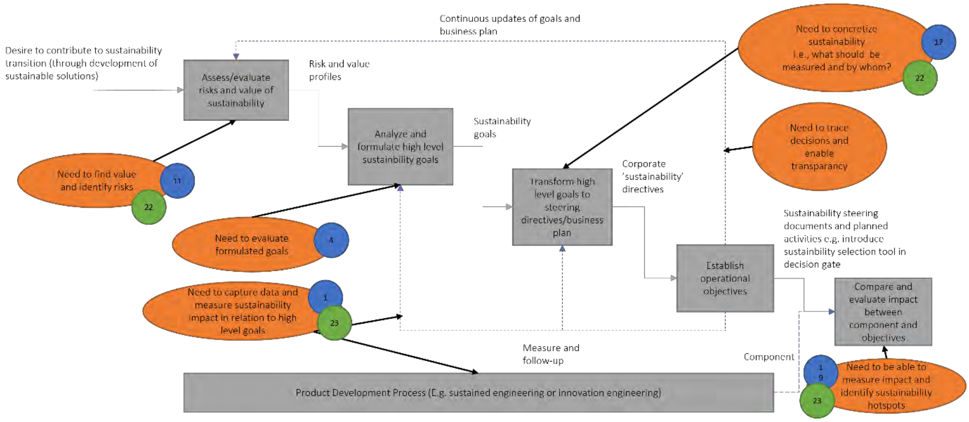
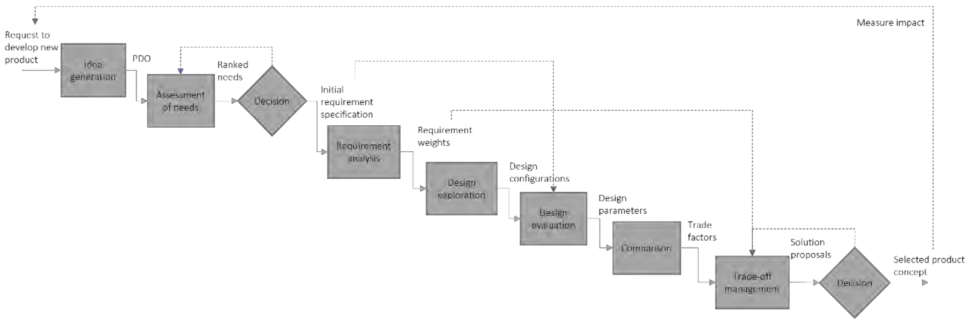


Case study D2 - Strategically integrating sustainability in the product innovation process

Outcome from Step 1 is the same as for case study D1

Outcome from Step 2

"Innovation engineering"
Today, the main share of design decisions are based on proven technical performance (Certificate/operating hours) and costs. The opportunities related to sustainbility are limited as a result of this. New processes and routines therefore need to be developed to allow sustainability to be part of the trade between performance parameters such as economy and enabling increased and sustainable long-term profitability. The processes and routines must include both standard products and customized solutions.



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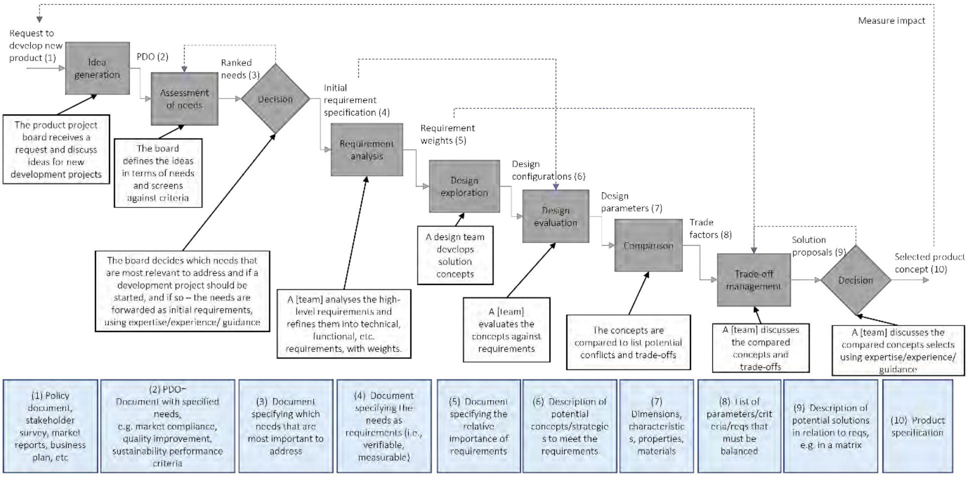

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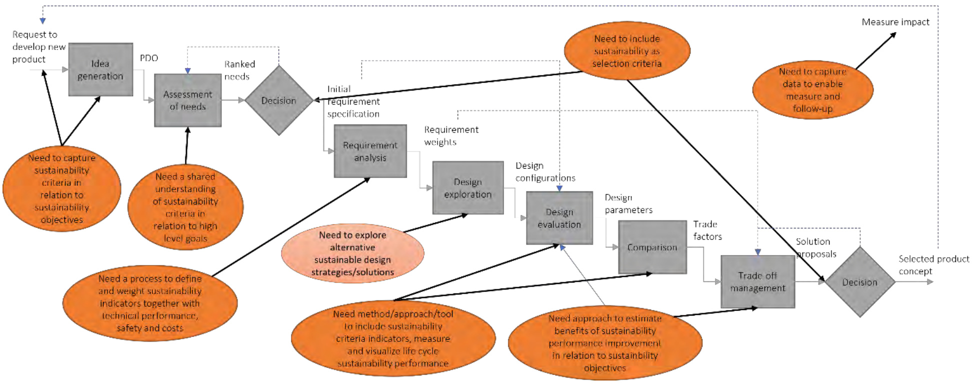


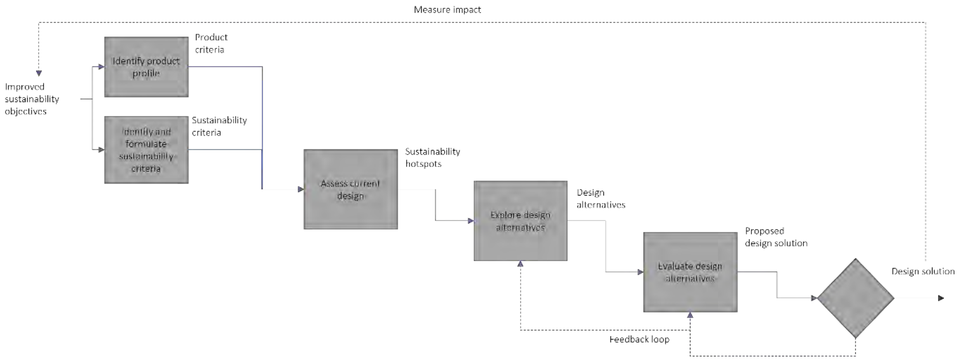
The outcome from Step 5 is missing, as Step 5 was introduced subsequently.

Case study D3 – Strategically integrating sustainability in incremental product development

Outcome from Step 1 is the same as for case study D1

Outcome from Step 2

"Sustained engineering"
Company D currently lacks a proactive maintaining process to manage its current product portfolio. Product revisions are only initiated when specific requirements are received or activated. This means no proactive or systematic approach to changes and improvement related to neither technical performance nor sustainability.



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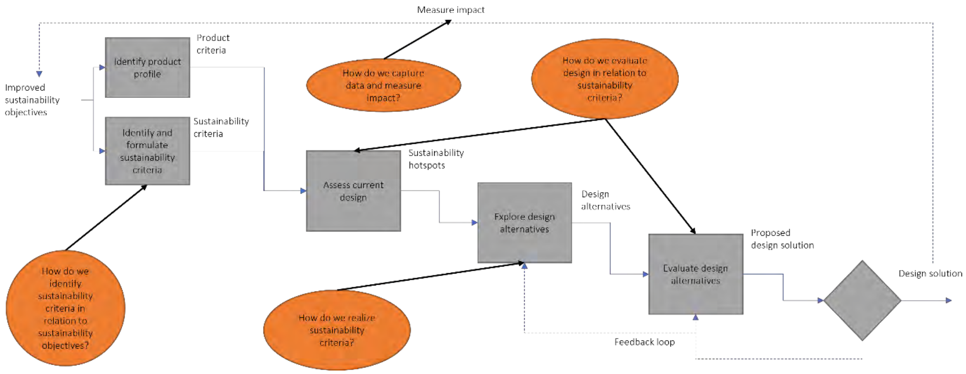
Outcome from Step 4



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