Thesis for The Degree of Licentiate of Engineering

On the adoption of design methods: Accelerating the sustainability transformation in manufacturing industry

Adam Mallalieu

Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden, 2024

On the adoption of design methods: Accelerating the sustainability transformation in manufacturing industry

ADAM MALLALIEU

Technical Report No. IMS-2024-9
Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Göteborg,
Sweden
Phone: +46(0)31 772 1000

Printed by Chalmers Digitaltryck,
Gothenburg, Sweden 2024.

On the adoption of design methods: Accelerating the sustainability transformation in manufacturing industry

Adam Mallalieu
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

The manufacturing industry requires a rapid shift and change of practices to align with sustainable production and consumption. This, together with emerging technologies, upcoming legislation, and changing market trends push for a so-called *sustainability transformation*. The notion of *sustainable design practices* has been identified and highlighted as a crucial enabler to succeed in such a transformation. At the same time, *design researchers* develop design methods that can support organizations to adopt *sustainable design practices* and accelerate such a transformation. However, the industrial adoption of such design methods is challenging, and their use remains under-utilized.

Research in the design domain tends to study this issue from a process and methodological perspective, often resulting in 'pragmatic' proposals on how developed design methods can be modified and adapted, or 'improved', to meet the needs of practitioners. Such an approach, however, often fails to appropriately consider organizational and human-behavioral aspects to *change*, which in turn have been more studied in the management research domain. This opens up for research considering these three perspectives simultaneously when studying the adoption of design methods. Qualitative empirical data focused on the adoption of *sustainable design practices* using design methods was therefore collected, using participatory observation in several case studies with actors from the manufacturing industry. Three literature studies complemented the empirical data collection to understand the topic further.

This thesis identifies five key barriers to the adoption of *sustainable design practices* using design methods: (i) The prescriptive nature of design methods combined with the influence of human-behavioral aspects; (ii) The contextual complexity of design method adoption; (iii) A *paradigm of product design* that persists in the manufacturing industry; (iv) The presence of *cognitive biases* that risk of leading to a state of *pseudo-sustainability*; (v) Insufficient information and data capabilities. Two new concepts were also introduced, referred to as the *dualism of design methods*, and the *situational design problem*. These two concepts clarify the role of design methods and explain the barriers to adoption. Finally, pathways for future research to address these key barriers were proposed, including approaches to *needs driven and contextually adapted adoption*, and *Sustainable design thinking*.

Keywords Design Methods, Sustainable Design Practices, Organizational Change, Designing, Sustainability Transformation, Engineering Design, Design Research

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper A**] S. Carlsson., **A. Mallalieu.**, L. Almefelt., J. Malmqvist., *2021, "Design for Longevity - A Framework to Support the Designing of a Product's Optimal Lifetime"*
Proceedings of the Design Society, Volume 1: ICED21, August 2021, pp. 1003-1012. 10.1017/pds.2021.100

Author contribution: I acted as a joint first author with Carlsson and took an equal part in planning and executing the research activities. I also took an equal part in planning and writing the paper with Carlsson. Almefelt supported the research and writing process, whereas Malmqvist supported the writing process.

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

Author contribution: I acted as a joint first author with Hajali and took an equal part in planning and writing the paper. I also took an equal part in planning and executing the research activities with Hajali. Isaksson and Panarotto supported the research activities and writing process.

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

Author contribution: I acted as the first author and took a leading role in planning and writing the paper. I also coordinated, planned, and facilitated the activities required to conduct the case study with

Martinsson Bonde and Watz. The remaining authors supported the research activities and the writing process.

[**Paper D**] **A. Mallalieu.**, A. Jonasson., S. Petersson., M. Rosendal., S. I. Hallstedt., L. Almefelt., O. Isaksson., *2024, "Sustainability Criteria for Introducing New Technologies in Low-Income Contexts"*
Proceedings of the Design Society, to appear in DESIGN2024, May 2024.

Author contribution: I acted as the first author and took a leading role in planning and writing the paper. Jonasson and Petersson planned, coordinated, and executed the case study, and developed the tool with the support of me, Rosendal, and Hallstedt. Hallstedt, Almefelt, and Isaksson also supported the writing process.

[**Paper E**] **A. Mallalieu.**, S. I. Hallstedt., O. Isaksson., M. Watz., L. Almefelt., *2024, "Barriers and Enablers for the Adoption of Sustainable Design Practices Using New Design Methods – Accelerating the Sustainability Transformation in the Manufacturing Industry"*
Paper in review for journal publication.

Author contribution: I acted as the first author and took a leading role in planning and writing the paper. I also took the leading role in collecting and analyzing the data with support from the remaining authors. The remaining authors also continuously supported the writing process.

Other publications

Four additional publications are part of this research. However, they are not appended to this thesis due to contents overlapping that of the appended publications.

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

[**b**] Hallstedt I S., Isaksson O., Watz M., **Mallalieu A.**, and Schulte J., *2022, "Forming digital sustainable product development support" Proceedings of NordDesign 2022, doi: 10.35199/NORDDESIGN2022.37.*

[**c**] Hajali T., **Mallalieu A.**, Brahma A., Panarotto M., Isaksson O., Stålberg L., and 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, Volume 3: ICED23, July 2023, p. 2315-2324.* doi: 10.1017/pds.2023.232

[**d**] Isaksson O., Brahma A., Hajali T., Ohlsson D., and **Mallalieu A.**, *2024, "The Importance of Digitalisation in Industrialising Additive Manufacturing: Learnings from the DIDAM P2030 Project" To appear in proceedings of the 11th Swedish Production Symposium, April 2024..*

Acknowledgments

I want to thank my supervisors Lars Almefelt and Ola Isaksson for their support and engagement in my research. I also want to thank my examiner Johan Malmqvist for always providing valuable feedback from a more external point of view. I am also thankful to my other close colleagues in the Systems Engineering Design research group on who I occasionally test many of my ideas. I also want to provide a special thanks to Matilda Watz and Sophie Isaksson Hallstedt, who I have worked closely with and learned a lot from during these initial stages of my Ph.D. journey. The same applies to my many other co-authors, colleagues, and collaborators outside of Chalmers University of Technology. This includes people from the case companies and colleagues at EWB-SWE and Blekinge Institute of Technology.

This research was supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) through the projects DSIP [2020-04163] and DiDAM [2019-05591].

I also want to provide a big thanks to my close friends and family, this would not have been possible without your being, and support. I would argue that my inner drive stems from thinking that everybody deserves an equal chance to live the life I do.

Contents

Chapter 1

Introduction

This chapter introduces the background, the research focus and context, the scope and delimitations of this research, and the overall structure of the thesis.

1.1 Background

Sustainability is a societal and systemic, or 'wicked problem' (Lönngren & Van Poeck, 2021), and we are reaching a critical stage where there will be irreversible effects if society continues on the same trajectory (Rockström et al., 2023; World Economic Forum, 2022; World Business Council for Sustainable Development, 2021). Parts of the global society are already facing severe consequences of how the society currently operates due to, for example, climate change (United Nations, 2022; Mutanga et al., 2013). This calls for a societal *sustainability transformation* on several levels, including the global economy, policies, business models, and the products we produce and consume. Furthermore, the manufacturing industry is responsible for a significant part of the global carbon emissions and energy consumption (World Economic Forum, 2023). Many of the manufactured products also emit greenhouse gases and consume energy post-production. Moreover, there are also other apparent issues such as inequalities across the value chain, and resource scarcity. This, in turn, highlights the need for a so-called *sustainability transformation* in the manufacturing industry, which requires radical changes in current practices (Bengtsson et al., 2018). There is much research ongoing, and resources are being targeted both nationally and internationally on how such organizations better can develop more sustainable solutions, i.e., achieve *sustainability transformation* (Produktion2030, 2024; European Commision, 2021; VINNOVA, 2024; ACARE, 2022). Trends and advancements in e.g., electrification, digitalization, and additive manufacturing, along with efforts towards a circular economy are seen as enablers to a *sustainability transformation.* Upcoming legislation and policies also aim to push the manufacturing industry towards such a transformation, including *The Science-Based Targets*, *The EU taxonomy*, *The Digital Product Passport*, *The EU green deal*, and *The End-of-life vehicles* *regulation* specifically for the automotive industry.

Design, or rather design practices, has been highlighted as a critical enabler for a *sustainability transformation* in the manufacturing industry (see e.g., Design Council, 2021; Sumter et al., 2020; Klotz et al., 2018). Moreover, the early design phases have been highlighted as critical where the ability to anticipate sustainability performance (i.e., both social, ecological, and economic) and design products with a lifecycle perspective is considered crucial to product development and manufacturing organizations (Bhander et al., 2003; Ramani et al., 2010; Hallstedt et al., 2023b). A *sustainability transformation* does however challenge current design practices in such organizations (Hallstedt et al., 2020; Ceschin and Gaziulusoy, 2019), and the manufacturing industry struggles to adopt *sustainable design practices* (Baldassarre et al., 2020; Vilochani et al., 2024). There is, for example, a lack of sufficient ecological and social considerations across the product's lifecycle in how design currently is practiced.

Previous research has shown that the appropriate adoption[1] of new and improved, or 'evidence-based', design methods proposed by design researchers can support the transformation of the manufacturing industry's current design practices to *sustainable design practices* (Faludi et al., 2020; Hallstedt et al., 2023a). Design researchers (Blessing and Chakrabarti, 2009; Gericke et al., 2022) propose several design methods to the industry but appropriate adoption has been proven difficult and remains under-utilized. This is the case for any design method (Eder, 1998; Gericke et al., 2020), but also for design methods focused on sustainability (Karlsson and Luttropp, 2006; Parolin et al., 2024). Several aspects related to the adoption of design methods focused on sustainability have been raised. Lindahl (2006) did for example highlight that such design methods need to be user-friendly. Parolin et al. (2024) highlights that the adoption of such design methods is limited due to a lack of access to data and information. There are also relevant insights from studies focused on the adoption of any design method, where Eder (1998) for example highlights the need for 'method champions' that refers to practitioners inside an organization that take a leading role in scaling the use of the design method. Gericke et al. (2020) introduce the concept of *method ecosystem* that refers to the organizational context where design methods must fit, and that design researchers must consider this context when developing, and proposing, design methods. López-Mesa and Bylund (2011) provide several insights into how the adoption of design methods can be facilitated but also highlight that it induces *change* to current design practices.

1.2 Research focus and questions

Considering aspects of *change* have been highlighted as critical to understanding the adoption of design methods but are also lacking appropriate consideration in literature focused on method development, and adoption (Geis et al., 2008; López-Mesa and Bylund, 2011; Booker, 2012; Jagtap et al., 2014; Pieroni

[1] 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.

et al., 2019). Furthermore, several previous studies focusing on the adoption of design methods tend to take a process and methodological focus, which often entails 'pragmatic' proposals on how to facilitate the adoption of design methods. This, for example, includes making the design methods easier to use, less time-consuming, or adapted to fit their current design practices, and seemingly bypassing the challenges of *change*. There have, on the other end, been several studies focusing on *change* with a focus on organizational and human-behavioral perspectives (see e.g., Kotter, 1995; DiMaggio and Powell, 1983) providing an understanding of why change can be challenging. Several of such studies do however treat *change* rather generically, and not sufficiently contextualized from a process and methodological perspective.

Furthermore, facilitating adoption with 'too pragmatic' proposals can pose a risk to a successful *sustainability transformation* in the manufacturing industry, leading to e.g., sub-optimal solutions. It is important to acknowledge the complexity of sustainability and the magnitude of changes required for the manufacturing industry to align with sustainable production and consumption (Bengtsson et al., 2018; Ceschin and Gaziulusoy, 2019). It is, for example, possible to argue that the manufacturing industry needs to adapt to *sustainable design practices*, and not vice-versa. Ultimately, this highlights the issue of studying the adoption with limited consideration from either of three perspectives, i.e., the process and methodological, organizational, and human-behavioral. In turn, this calls for research that simultaneously considers these three perspectives while studying the adoption of *sustainable design practices* using design methods. Figure 1.1 frames this figuratively and highlights that this research encompasses different perspectives.

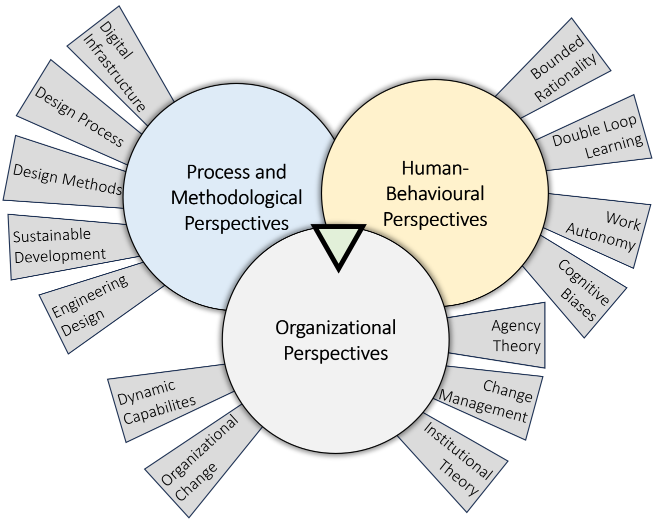

Figure 1.1: Illustration of the interdisciplinary scope of this research. The large circles represent the three perspectives that will be considered, where different theories can be utilized. The green triangle represents a better understanding of the adoption of design methods when considering these perspectives simultaneously.

This research aims to increase understanding of what currently limits adoption, how to facilitate adoption, and how design methods can increase an organization's ability to design more sustainable solutions. This thesis thus focuses on design methods that have been developed to accelerate a *sustainability transformation* in the manufacturing industry. Furthermore, this research intends to explore the topic of design method adoption and provide both new insights, but also frame previous insights further contextualized to the process and methodological context of *sustainable design practices*. Three research questions are formulated to support this research in fulfilling this aim.

- RQ1: What barriers influence the adoption of *sustainable design practices* using new and improved design methods?
- RQ2: How can new and improved design methods support accelerating organizations' *sustainability transformation*?
- RQ3: How can the adoption of new and improved design methods be facilitated?

RQ1 is descriptive and intends to enable new insights to be captured but also frame previous insights in the specific context of *sustainable design practices*. This is of interest since design method adoption has been studied previously but is a persisting challenge within the design domain.

RQ2 is prescriptive in its formulation, but descriptive in its intent and is formulated on the assumption that adoption is challenging. The question intends to capture how design methods, not exclusively via adoption, can be used as a means to support product development and manufacturing organizations in their *sustainability transformation*.

RQ3 is also prescriptive and focuses on how adoption can be facilitated. This question intends to capture relevant insights into the adoption of any design method and provide guidance as to how different means can facilitate the adoption.

1.3 Research context

The research context utilized in this research can be divided into three different empirical settings.

Project A - Digital Sustainability Implementation Package: This research project focused on demonstrating industrial actors' ability to adopt *sustainable design practices* using design methods proposed by design researchers. The project included two research groups that develop such design methods, *Systems Engineering Design* at Chalmers University of Technology, and Strategic Sustainable Development at Blekinge Institute of Technology. The project involved large actors in 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 solution provider (Eurostep). The project also paid specific attention to the *digital infrastructure* across the complete value chain. The period spanned from April 2021 to February 2023.

Project B - Demonstration of Infrastructure for Digitalization enabling industrialization of Additive Manufacturing: This research project focused on demonstrating industrial actors' ability to industrialize additive manufacturing using computerized design methods. The project included several research groups that develop such design methods, *Systems Engineering Design* and *Powder Metallurgy and Additive Manufacturing* at Chalmers University of Technology, and research groups focusing on additive manufacturing at RISE (Research Institutes of Sweden). The project involved large actors in the manufacturing industry (Volvo Group, Volvo Construction Equipment, Epiroc, Uddeholm, Brogren Industries AB), and a solution provider (Eurostep). The project also paid specific attention to the *digital infrastructure* across the complete value chain. The period spanned from April 2021 to May 2023.

Engineers Without Borders-Sweden (EWB-SWE): This is a Swedish non-governmental organization (NGO) with 500+ volunteering members working focusing on sustainable development. EWB-SWE, for example, carries out international projects across several low-income countries, or what EWB-SWE phrase as *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 collaboration between EWB-SWE and the author was initiated to study how the adoption of design methods can support EWB-SWE's efforts, and more effectively contribute to sustainable development. The collaboration started in April 2022 and is still ongoing, and has involved both internal improvement projects, along with online and on-site activities. The activities have mainly focused on understanding where and how design methods can be used to further improve EWB-SWE's humanitarian engineering efforts.

Project A has served as the largest contributor to this research, whereas Project B and the activities carried out at EWB-SWE are used to complement and generalize the findings further.

1.4 Scope and delimitations

Some delimitations need to be listed to clarify the scope of this thesis.

- This research focuses on the manufacturing industry whereas the studied topic can be considered relevant in other sectors in need of developing more sustainable solutions.

- The research scope is not derived from an identified gap in theory or literature, but from a practical gap identified in the empirical sample.

- This research includes the consideration of organizational and human-behavioral perspectives to a level where previous theories are used to better understand and explain the adoption of design methods. However, this thesis does not aim to contribute to new knowledge within organizational, or human-behavioral disciplines, such as cognitive sciences, or organization theory.

- The design methods utilized in this research have been developed and evaluated before this research. It is therefore not within the scope of this thesis to further asses or evaluate how each design method performs in meeting its specific goals. This thesis is therefore also based on the assumption that the appropriate adoption of these design methods can accelerate a *sustainability transformation*.

1.5 Thesis structure

This chapter has briefly introduced the reader to the problem and focus of this research. Chapter 2 outlines the Research Approach adopted in this research. Chapter 3 presents the frame of reference to the studied topic. Chapter 4 presents the results from the appended papers along with highlighting their contribution to this thesis. Chapter 5 discusses the findings with respect to the RQs and the validity of the results. Chapter 6 concludes the main findings and presents the way forward. The reference list is provided at the end followed by the appended papers that this research is founded on.

Chapter 2

Research approach

This chapter presents the overall research structure, clarifies the study objects, brief epistemological considerations, how data was collected and analyzed, and considerations concerning the validity and ethics of this research.

2.1 Research on design

Research on the design activity is commonly referred to as either *design research* (see e.g., Blessing and Chakrabarti, 2009; Gericke et al., 2022), and/or occasionally design science (see e.g., Fuller, 1957; Gregory, 1966; 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 process of designing, and strives to produce new knowledge relevant to improve 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, p. 323) 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."

Blessing and Chakrabarti (2009, p. 5) 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". An interpretation of such research is visualized in Figure 2.1 (on the next page) where the design process is further broken down into several smaller design activities

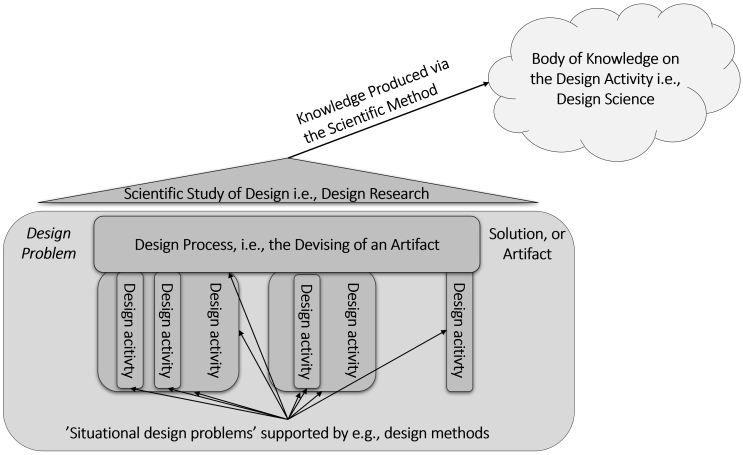

Figure 2.1: Interpretation of how a scientific study of the design activity leads to a body of knowledge to better understand design.

2.2 Research structure

This research adopts a qualitative approach (Creswell, 2014) using a wide set of methods aimed to explore the studied topic from all three perspectives (i.e., process and methodological, organizational, and human-behavioral). Qualitative observations and multiple case studies (Säfsten & Gustavsson, 2020) serve as the base for collecting empirical data across the empirical settings, complemented with theoretical sampling using questionnaires focused on different themes that emerged across the case studies. Three literature studies have also been carried out with different focuses and more narrow scopes.

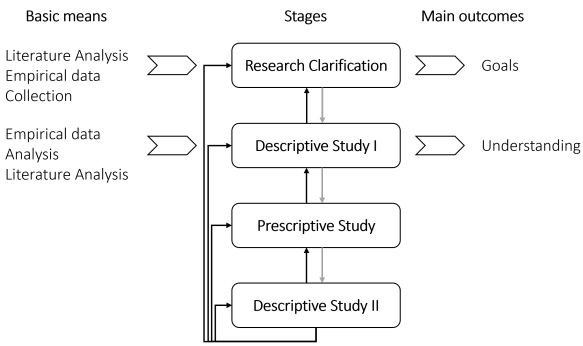

Figure 2.2: The research focus of this thesis visualized according to the *Design Research Methodology* (Blessing & Chakrabarti, 2009).

The *Design Research Methodology* (Blessing & Chakrabarti, 2009) (DRM) is commonly used to structure and guide design research. It has not been used actively in this research but does however act as an effective means for visualizing the focus of this research in retrospect. The emphasis has been on the two initial phases, as visualized in Figure 2.2. Initial literature studies were used to understand the problem, whereas early data collection supported framing the problem further, which led to the interdisciplinary scope of this research. Furthermore, analyzing the collected data, and comparing the empirical findings to literature resulted in a better understanding of the problem's interdisciplinary nature. The research findings, so far, mainly address RQ1 and RQ2, whereas RQ3 is less touched upon, as Table 2.1 illustrates. This thesis thus paves the way for the final phases of the DRM, focusing on developing and evaluating support that aims to address the identified problems or barriers.

Table 2.1: Paper A-E's contribution to the RQs.

Research questions \ *Papers*	Paper A	Paper B	Paper C	Paper D	Paper E
RQ1: What barriers influence the adoption of sustainable design practices using new and improved design methods?	X	X	X	X	X
RQ2: How can new and improved design methods support practitioners in their organizations' sustainability transformation?			x		X
RQ3: How can the adoption of new and improved design methods be facilitated?		x	x	x	x

Paper A consists of a literature study of design methods focused on sustainability with specific attention to lifecycle thinking and product lifetime. Further, the paper identifies barriers and gaps in the literature. Paper A also disseminates the development and evaluation of a framework, this framework is however not part of the scope of this thesis.

Paper B consists of a systematic literature review of developed *design for additive manufacturing* tools and pays specific attention to aspects related to the *digital infrastructure*. Further, a case study in Project B was also carried out in this paper to study practical implications concerning the digital *infrastructure*.

Paper C consists of a case study in project A and investigates potential barriers to integrating sustainability criteria in a design space exploration method. Further, a new approach to facilitate the adoption of design methods is also utilized in this paper.

Paper D consists of a literature study and empirical study using EWB-SWE, focusing on how to achieve a sustainable introduction of new technologies in low-income contexts. Further, one of the design methods available in project A is proposed, empirically evaluated, and adapted to EWB-SWE.

Paper E consists of the collection of empirical qualitative data in Project A that is analyzed using *Glaserian Grounded Theory*. This results in a descriptive framework capturing interdisciplinary factors influencing the adoption of *sustainable design practices* using new and improved design methods. Further, the findings are compared to literature to explain and clarify the findings, entailing *systemic barriers* and propositions.

2.3 Study objects

Design methods are one of the main study objects in this research, treated as passive objects, or constructs, used to support the design of solutions or artifacts. There were several design methods available in Project A developed by the two research groups, and these 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 practices* as defined in this research. The design methods, in this research, thus represent the 'ideal' or theoretical process and methodological context of *sustainable design practices*. A *design method* as such will be further described in the Frame of Reference. The design methods used in this research are, in this thesis, divided into two main categories.

Category one: *Systems Engineering Design* (SED) design methods, based on more than 20 years of research in close collaboration with the Swedish manufacturing industry (see e.g., Isaksson et al., 2000; Isaksson et al., 2013; Borgue et al., 2021). The SED design methods aim to support the modeling and design of complex systems or solutions where there are several dependencies and interactions between different domains and sub-systems. For example, different functions in the system, stakeholders in the system, and/or engineering disciplines utilized in the system. These dependencies are 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 typically involves the collection of data and information from different stakeholders in the organization, which later is incorporated and/or modeled in computer-based tools by either a design researcher or practitioner, or what is referred to as a *method expert*. The outcome is later communicated and utilized across the organization to enable more information-based design decisions.

Category two: *Sustainable Product Development* (SPD) design methods and are based on more than 15 years of research in close collaboration with the Swedish manufacturing industry (see e.g., Byggeth and Hochschorner, 2006; Hallstedt et al., 2013; Watz and Hallstedt, 2022). The SPD design methods aim to support the strategic integration of socio-ecological sustainability in product development and manufacturing organizations. These design methods utilize the *Framework for Strategic Sustainable Development* (Broman & Robèrt, 2017) and strive to ensure that a full systems perspective is incorporated in the early phases of design. The design methods support practitioners in e.g., anticipating the sustainability performance of different solutions, identifying sustainability-related risks, and guidance towards more sustainable solutions. Applying the SPD design methods typically involves a 2-3 hour facilitated workshop using a multidisciplinary team of practitioners where a set of key questions or focused topics are discussed. This team ideally includes different designers, experts, and/or specialists inside the organization. The output from this is later consolidated either by researchers or practitioners, or what is referred to as a *method expert*. The outcome is later communicated and used by relevant stakeholders inside and outside the organization.

Practitioners inside the organization serve as the *designers* (Simon, 1969), and users of the design methods. The practitioners also represent their organization from their perspectives. This ensures that the organizational and human-behavioral perspectives in the specific process and methodological context of *sustainable design practices* are treated in this research. This dual view of practitioners supports the exploration of challenges related to both their organization's ongoing *sustainability transformation*, and also the adoption of any new design methods as such.

The product development and manufacturing organizations also serve as study objects. The organizations are in this study represented by the practitioners as a collective. This can, for example, relate to the collective behavior of practitioners, and/or what practitioners as a collective say about the organization, e.g., that practitioners generally are occupied, or similar. The organizations can also be represented and understood from e.g., documents that represent the organizations' values, processes, and tools. This ensures that the organizational perspective is under consideration in the specific process and methodological context of *sustainable design practices*.

Design researchers are also treated as study objects in this research, divided into two roles: (i) *Method developers*, i.e., the ones that have developed the design method; and (ii) occasionally as the role of *method experts*, i.e., an individual considered an expert in using the design method. These two roles are also important to consider as it is interesting to study and understand how adoption is facilitated currently by design researchers, or *method developers* and/or *experts*. It is, however, not necessarily design researchers that need to take the role of *method experts*, but did in many instances when the design methods were completely new to the organizations. This meant that there were no *method experts* in the organizations available.

2.4 Epistemological considerations

Different schools of thought are adopted in this research including elements from both *interpretative* and *positivist* assumptions. As mentioned, design research lies in the intersection of natural sciences and social sciences, which historically have adopted different schools of thought (Guba and Lincoln, 1994; Creswell, 2014). Three guiding criteria were therefore applied to guide the data collection and analysis.

The first criterion focused on adopting a *hermeneutic* tradition and adds a dimension of understanding and ensures the *interpretative* assumptions (Age, 2011), i.e., the collected data should be interpreted and understood in its context when assigned meaning or codes.

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

A third criterion was adopted to limit the data collection and focused on adding a dimension of usefulness, which aligns with the *pragmatism* tradition (Age, 2011). The collected data or assigned meaning should be useful to the studied topic. This strategy was added since the data collection otherwise risks exploding due to the wide scope of this research (Walker & Myrick, 2006).

Furthermore, this makes it relevant to acknowledge the researcher's bias and potential influence on this research. Both in the sense that the researcher determines what is considered *useful*, but also occasionally *interpreting* what is happening directly influencing the results. This will be further clarified below when describing the data collection process and how research validity was considered. The adopted lens towards *sustainable design practices* is also further described in the Frame of Reference to clarify the process and methodological context in more detail. The author had no prior knowledge of the design methods as such but an academic background in mechanical engineering and design with a particular focus and interest in sustainability, and a minor academic background in business administration.

2.5 Data collection

Data has been collected using different methods. Three literature studies have been carried out with different focuses. Empirical data was collected using participant observation and questionnaires in the research context.

2.5.1 Literature study

Three literature studies have been carried out, summarized in Table 2.2.

The **first literature study** was carried out in the study found in paper A. This search focused on sustainable design with a focus on product lifecycle thinking and product lifetime optimization. This approach focused on finding a gap in the literature regarding ways to implement these two approaches in design practice. Keywords related to these topics were used to scan for literature across literature databases. The search was considered to be saturated when a clear gap in the literature was identified.

The **second literature study** was carried out in the study found in Paper B. This search focused on design methods embodied as computerized tools or software aimed to support designers in designing for additive manufacturing. Scopus was used to search for literature using the following text string "((additive AND manufacturing) OR (3d AND printing) AND (digital OR data) AND design AND (tool OR method))". 209 publications were in total identified, but systematically narrowed down to 44 articles. This enabled a gap analysis regarding how design researchers treat the *digital infrastructure* during the development of their tools.

The **third literature study** was carried out in the study found in Paper E. This search focused on literature that provides both theory and previous studies on design method adoption with either and/or process and methodological, organizational, and human-behavioral perspectives. The intention was to identify literature that can be used to further explain and clarify the empirical findings to frame the adoption of design methods from all three perspectives. The search was considered saturated when the empirical findings were deemed to have plausible explanations and were clarified sufficiently.

Table 2.2: Summary of literature studies carried out in papers A, B, and E.

Paper	*Literature study focus*
Paper A	Design methods and previous studies on sustainability with a focus on lifecycle thinking and product lifetime optimization
Paper B	Design for additive manufacturing tools developed and proposed by academia and how these consider information and data management aspects
Paper E	Interdisciplinary literature providing theory and studies on the adoption of design methods from either and/or both process and methodological, organizational, and human-behavioral perspectives

2.5.2 Participatory observation study in the research context

Empirical qualitative data was systematically collected in Project A since it is the empirical context that aligns with the scope of this research. Empirical qualitative data was, however, also occasionally collected in Project B and EWB-SWE to generalize the findings. The researcher took part in several different activities inside Project A and Project B acting as a coordinator, responsible for the interaction between practitioners and the design researchers. In turn, this enabled the researcher to study the interaction between practitioners and *method developers* and/or *experts*, which is of interest. The researcher did not directly influence the responses or actions aimed to be captured, but mediated and facilitated many of the activities. Two figurative examples of these activities are illustrated in Figure 2.3 on the next page.

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" (2020, p. 146). The observations are *direct* and *unstructured* (Säfsten & Gustavsson, 2020). It is worth acknowledging that this approach is close to *Action research* (Säfsten & Gustavsson, 2020). However, this research has, so far, not led to any actions taken that will address the studied problem.

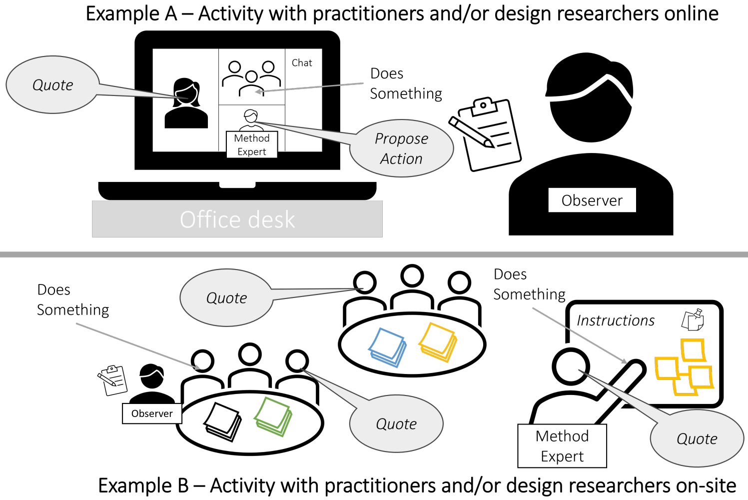

Figure 2.3: Figurative examples of scenarios illustrating how data was collected using observations.

The data was more specifically collected using qualitative observations (Creswell, 2014) capturing codes in the format of in-vivo (Miles et al., 2014) in notebooks. Figure 2.4 provides an example of the collected data and also illustrates how the collected data managed to capture all three perspectives, and this particular example resulted in six separate codes.

Data was collected for almost two years in Project A, alone, and resulted in roughly five full notebooks, where each notebook included 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 similar to Figure 2.4. The collected data can in turn be distinguishable into four different categories:

- Quotes either from a researcher or a practitioner.
- Observations of concrete events by either a researcher and/or a practitioner.
- Notes of something that a researcher or practitioner 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 practitioner.
- 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.

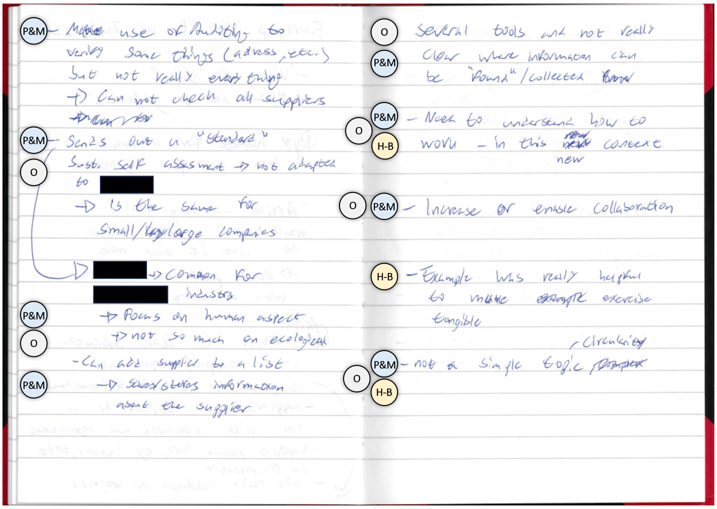

Figure 2.4: Example of raw data captured in a notebook during an informal meeting with a practitioner. Blue circles represent codes that capture a process and methodological perspective (P&M). Yellow circles represent codes that capture a human-behavioral perspective (H-B). White circles represent codes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

Different activities in Project A resulted in the possibility of collecting empirical data. A multiple case study approach (Säfsten & Gustavsson, 2020) using three of the companies available in Project A served as the main means for collecting data. The case studies are summarized in Table 2.3 on the next page. All activities that involved participant observations in Project A are listed and summarized below.

- 30 workshops were carried out across multiple case studies. These corresponded to the appropriate use of many of the proposed design methods, as they were briefly described in Section 2.3.

- More than 20 recurring bi-weekly meetings varying between 30 to 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 required data and information were available during the workshops. These meetings also, commonly, involved practitioners elaborating on issues they are facing, and opportunities they see regarding their organization's *sustainability transformation*. 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 where results from the workshops were consolidated, or activities used to adapt the design methods to the company case and context.

- Four seminars were carried out in Project A with the full project consortium. The seminars were of a duration of five to ten hours and included focused discussions in larger groups about different emerging topics concerning the studied topic.

Table 2.3: Summary of the multiple case studies in Project A.

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

The utilized case companies in Project A were chosen on the basis that they represent: (i) International product development and manufacturing organizations; and (ii) Organizations that have an expressed ambition to design and manufacture more sustainable solutions, and thus transform current design practices to *sustainable design practices*.

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 were with different scopes and performed with different functions within the organization but both within 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 how to integrate sustainability in their product innovation process, where a steel frame was used as the case product.

Company C is a large manufacturer in the automotive sector. Three different cases were carried out with this company, but two had several joint activities, namely cases C1 and C2 (see Table 2.3). The scope of these was deemed to be aligned and required tighter collaboration between the two business functions (product design, and procurement and sourcing). This required participants from several different functions since product design and procurement and sourcing are treated as two different 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.

2.5.3 Questionnaires

More than ten questionnaires were sent out in Project A. This was done either during or in preparation for the seminars to obtain individual practitioner responses on the topics discussed during the seminars. The questionnaires mixed free-form questions with quantitative questions.

2.6 Data analysis

The empirical data was analyzed in two iterations. The first iteration utilized *Glaserian Grounded Theory* analysis (Charmaz, 1996; Walker and Myrick, 2006). This approach inductively frames interdisciplinary factors that influence the adoption of *sustainable design practices* using new and improved design methods, captured in a descriptive framework. A second iteration focused on comparing the output from the *Glaserian Grounded Theory* analysis to previous literature to further clarify and explain the empirical findings. This analysis was thus able to provide answers to all RQs as it framed both barriers and enablers.

2.6.1 Glaserian grounded theory

Glaserian Grounded Theory was used to analyze the empirical data since it has *interpretative* as well as *positivist* assumptions and has a strong history in qualitative research (Charmaz, 1996). This aligns with the scope and aim of this research as it allows both different and novel themes to emerge and further strengthens the exploratory and interdisciplinary scope of this thesis. *Glaserian Grounded Theory* analysis consists of three main steps: *open coding*; *selective coding*; and *theoretical coding.* The overall process is visualized in Figure 2.5. As illustrated there, 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.

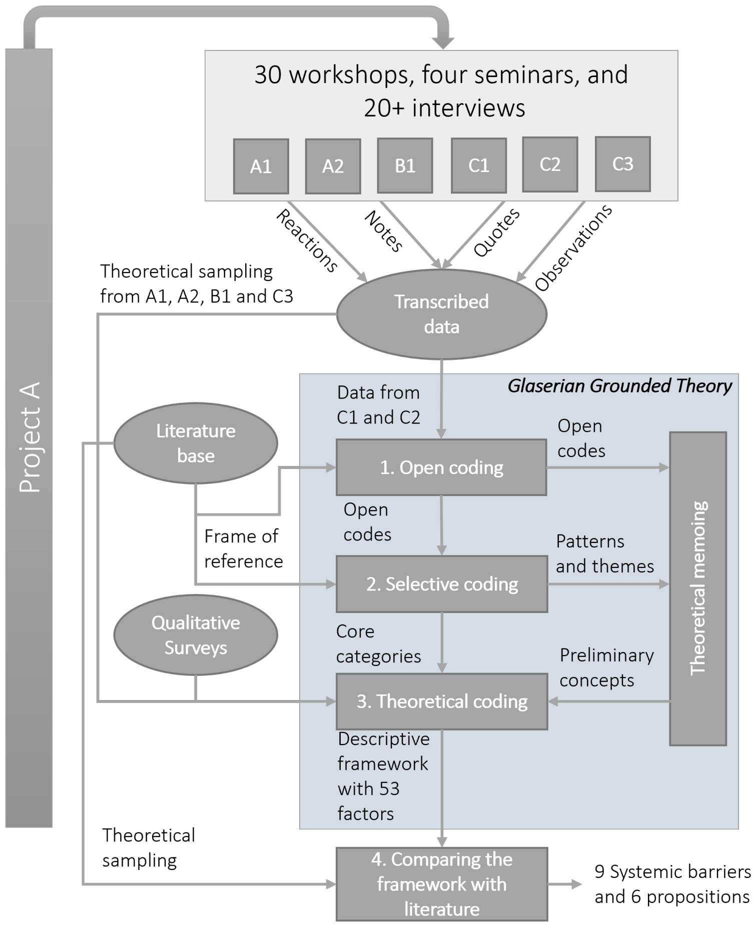

Figure 2.5: Analysis procedure of the collected empirical data in Project A.

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 the epistemological considerations are appropriately maintained.

1. The codes correspond to the data (*positivism*).
2. The data is interpreted and understood in its context when assigned codes (*hermeneutics*).
3. The codes are useful (*pragmatism*).

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). Furthermore, data from the remaining cases was in this step included to:

- 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.

Table 2.4 provides an example of how the raw data is assigned *open codes*, and later placed in more abstract *core categories* (i.e., selective codes).

Table 2.4: 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

2.6.2 Comparing the empirical findings to literature

The final step of the analysis focuses on how the findings compare and relate to literature (Charmaz, 1996, p. 47). This step added further nuance and depth to the empirical findings where literature from the third literature study was used. This analysis, in turn, resulted in a set of what is referred to as *systemic barriers* and propositions in Paper E. The intention was to make the empirical findings, as framed by the 53 factors captured in the descriptive framework, more easily absorbed and managed.

2.7 Research validity

Ensuring the validity of the findings in qualitative data analysis is of high importance, where several strategies can be used. Some of the *tactics* proposed by Miles et al. (2014) "for generating meaning" are 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.*

It is furthermore also of relevance to ensure the reliability and validity of the findings (Creswell, 2014; Säfsten and Gustavsson, 2020). Several strategies have been used to strengthen the validity of the findings further.

- The three criteria used to ensure correspondence, understanding and interpretation, and usefulness, during the data collection and analysis procedure.
- *Triangulation* (Creswell, 2014) by using multiple case studies in the context in focus. This is also further complemented by two other empirical contexts that can further strengthen the 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 is difficult since one researcher, for the main part, has been involved in collecting and analyzing the data. Furthermore, involving elements from *hermeneutics*, and *pragmatism* also influences the ability to ensure the reliability of this research. Transparency in the documentation of the collected data and analysis has been one approach to counter this, as it makes it possible to scrutinize the procedure externally and revisit the raw data. There is also transparency regarding the interaction between the researcher and the study objects of this research. Peer debriefing also supports increasing the inter-rater reliability of the findings (Säfsten & Gustavsson, 2020). Aspects of validity will be treated further in the Discussion.

2.8 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 point of view is that the study objects are confidential and 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 be less concrete. 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, including perspectives on different facets of design and design methods. The lens adopted towards *sustainable design practices* is also clarified. A set of relevant theories on *change* and *organizational learning* (an important facet in understanding *change*) with a stricter organizational, and human-behavioral focus are also presented. Finally, previous research on the adoption of design methods from the design domain is also presented with concluding remarks.

3.1 Design processes and the early phases of design

There have been many proposed views of what constitutes a design process (Ullman, 1992; Pahl et al., 1996; Eder, 1998; Ulrich and Eppinger, 2016). Ullman (1992, p. 16) 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, p. xxix) 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, p. 356), 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, p. 12) defines such a process as the "sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product".

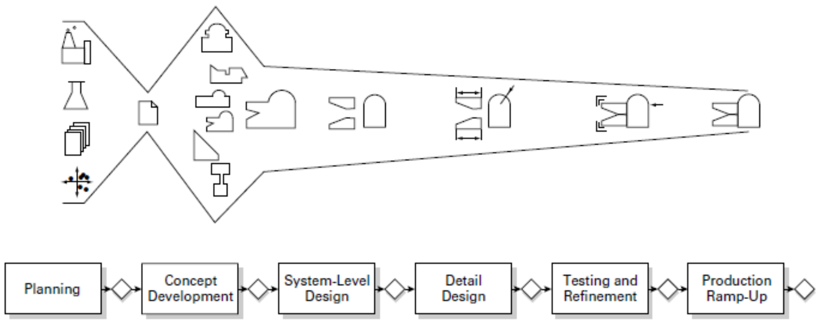

Figure 3.1: Illustration of a product development process (Ulrich & Eppinger, 2016).

Eder (1998) refers to (i) and (ii) as the 'early stages' of designing claiming that most impact on the final product is made there. Furthermore, terms such as the *fuzzy front end* (see e.g., Herstatt and Verworn, 2004; Reid and De Brentani, 2004) are occasionally used for what is referred to as the early phases of design in this thesis. 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 considered critical to developing sustainable solutions (Bhander et al., 2003; Ramani et al., 2010; Hallstedt et al., 2023b). Ullman (1992, p. 18) 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".

3.2 Designing as human activity

Simon (1969) stated that "everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (p. 111) and that designing "is concerned with how things ought to be, with devising artifacts to attain goals" (p. 114). Gregory (1966, p. 3) 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. Pahl et al. (1996, p. 1) claim that from psychological respect, "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". The process of designing as such is a cognitive or mental activity (Pahl et al., 1996; Simon, 1969) and has been further studied in what is referred to as cognitive psychology (Ullman, 1992; Simon, 1969).

Asimow (1962) views designing as the cycling between problem formulation, synthesis, and evaluation. Jones (1992) deconstructs designing into three modes diverging, transformation, and converging, which can be regarded as different modes of acting or thinking when designing. The Design Council (2005), for example, depicts designing effectively using a double diamond, where designers work iteratively between a problem and solution space in a diverging-transforming-converging manner. Aspects of designing have been recorded to occur in writing letters and making up names (Thomas & Carroll, 1979). A design can be a light bulb, a business, a production setup, a cogwheel, 'the best passage to work', or a complex situation in military contexts (see e.g., Banach and Ryan, 2009).

In the context of engineering design, Pahl et al. (1996, p. 1) state that "design is an engineering activity that provides the prerequisites for the physical realisation of solution ideas". In this thesis, designing or any design process is in essence viewed as a knowledge-producing process where different design activities support designers to better understand the problem as well as the potential solutions to that problem. Dorst and Cross (2001) refer to this as the co-evolution of problem-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" (p. 4) stating that designing goes beyond the "search within a problem space ... the designer constructs the design world within which he/she sets the dimensions of his/her problem space, and invents the moves by which he/she attempts to find solutions" (p. 11). 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). Designing as a human activity can also be claimed to cover much of the product development activities carried out within an organization but ultimately depends on what lens and resolution is used towards designing and the design process Eckert et al. (2023).

3.3 The complexity of design problems

Designing, or a design process, is typically needed to treat *design problems*, i.e., ill-structured, ill-defined, and unique problems (Simon, 1969; Archer, 1979;

Dorst, 2006; Gericke et al., 2022), or 'wicked problems' (Rittel and Webber, 1973; Buchanan, 1992). Rittel and Webber (1973, p. 161) list the ten following characteristics for such 'wicked problems'.

- There is no definitive formulation of a wicked problem.
- Wicked problems have no stopping rule.
- Solutions to wicked problems are not true-or-false, but good-or-bad.
- There is no immediate and no ultimate test of a solution to a wicked problem.
- Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
- Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
- Every wicked problem is essentially unique.
- Every wicked problem can be considered to be a symptom of another problem.
- The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution
- The planner has no right to be wrong.

There have also 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). (ii) The *design problem* can only be fully understood in the light of the solution, or as Cross (1992, p. 6) states "a design solution is not an arbitrary construct – it usually bears some relationship to the problem as given". Marples (1961, p. 64) 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 adds further nuance to *designing*, as depicted in Section 3.2, 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 benefit from applying *designerly ways of knowing*, *thinking*, and *acting* (Cross, 1982; Dorst and Cross, 2001; Dorst, 2011; Cross, 2023a). Furthermore, it is also suggested that many of the developed products today can be seen as parts of larger complex and evolving systems (Isaksson et al., 2023), which further underpin the growing complexity of the *design problems* organizations are expected to solve. 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'. Moreover, the *paradigm of design thinking* (Brown et al., 2008) has, for example, effectively utilized these insights of design or *designerly ways of knowing*, *thinking*, and *acting* (Cross, 1982; Cross, 2023a) to revolutionize problem-solving activities on a broader level outside of its origin within architecture and "product design" (Verganti et al., 2021; Auernhammer and Roth, 2021).

3.4 Sustainable development and sustainable design practices

Brundtland (1987, p. 292) defined *sustainable development* as "meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their needs". *Design* has been identified as an enabler of sustainable development efforts (see e.g., Klotz et al., 2018). The notions of a design process, *designing* as a human activity, and *design problems*, as presented above, support underpinning and clarifying why *design*, as a process and/or ability, can play a crucial role in developing sustainable solutions and contribute to sustainable development. However, appropriately incorporating ecological, social, and economic sustainability considerations in the design process remains a struggle for the manufacturing industry (Vilochani et al., 2024). It has, for example, been argued that this, in turn, also requires appropriate skills, knowledge, and adoption of several design methods (Faludi et al., 2020; Hallstedt et al., 2023a).

Research focused on sustainable design has proposed several approaches describing how ideal processes for sustainable design should be structured. For example, Ceschin and Gaziulusoy (2016) propose a framework that synthesizes research within the field of what they refer to as Design for Sustainability. This framework 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. Moreover, research has also presented several approaches to implementing eco-design and sustainable design processes (see e.g., Pigosso et al., 2013). Examples involve generic frameworks and tools to implement eco-design or circular design processes, and separate tools, methods, or strategies to support specific design tasks or design decisions. For example, the 9R framework (Potting et al., 2017), and can guide how to design more 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 what is referred to as Design for Environment, which focuses on how to minimize the environmental impact of products.

Wiek et al. (2011) outlined a set of competencies needed in efforts addressing sustainable development:

- Systems thinking competencies, i.e., the ability to analyze systems more holistically.
- Anticipatory competencies, i.e., the ability to predict performance and outcomes.
- Normative competencies, i.e., the ability to specify sustainability and negotiate it.
- Strategic competencies, i.e., the ability to strategically implement sustainability.
- Interpersonal competencies, i.e., the ability to motivate and facilitate collaboration.

Baldassarre et al. (2020, p. 2) broadly define sustainable design as "a rational and structured process to create something new for solving sustainability-related problems" and argue that a complete transformation to *sustainable design practices* is a matter for the whole organization. Sala et al. (2015, p. 315) highlighted the challenge of understanding "what contributes to a sustainable development and what does not". This thesis utilizes the *Framework for Strategic Sustainable Development* (FSSD) (see e.g., Broman and Robèrt, 2017) to frame how design, or sustainable design, can contribute to sustainable development. This framework includes eight principles that define socio-ecological sustainability and need to be considered throughout a design's, or product's, full lifecycle to contribute to sustainable development. Examples of different lifecycle phases are use, disposal, material extraction, and distribution.

These eight principles are explicitly defined (Broman & Robèrt, 2017, p. 23): "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 on how to adopt a strategic approach towards sustainable development. This 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.

Following this, *sustainable design practices* is in this thesis defined as:

> The appropriate incorporation of the *Framework for Strategic Sustainable Development* and *designerly ways of knowing, thinking, and acting* in an organization's design process.

Adopting *sustainable design practices*, in turn, strive to ensure that the developed solutions comply with the eight socio-ecological principles of the FSSD throughout their full lifecycle.

3.5 Clarifying design methods

Design methods are one of the main study objects of this research, and the use of this term is widespread and explicitly defined and referred to differently (see e.g., Bunge, 1966; Niiniluoto, 1993; Araujo, 2001; Aken, 2004; Gericke et al., 2022). Cross (2023b, p. 46) 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, p. 45) argued that design methods are "attempts to make public the hitherto private thinking of designers; to externalize the design process" and Eder (1998, p. 366) also describes them as "prescriptive knowledge as advice about designing ('know-how')". Wallace (2011, p. 242) 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. Gericke et al. (2022, p. 11) provide further nuance to what design methods are:

> "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".

Gericke et al. (2022) also separate the term design method from a tool and claim that tools instead (sometimes) can be used as means to facilitate the adoption of a design method.

Design researchers, see e.g., Blessing and Chakrabarti (2009) and Gericke et al. (2022), propose a plethora of prescriptive design methods, commonly referred to as 'formalized', 'theory-based' and/or 'industry best practices' (Eder, 2009). The overarching goal of any such design method is to support that better products are proposed following the design process (Cross, 2023b; Blessing and Chakrabarti, 2009). Design methods are typically developed by a design researcher. The DRM is a commonly used research methodology for developing such artifacts (Blessing & Chakrabarti, 2009). DRM is an iterative process that consists of four generic steps: (i) Research clarification; (ii) Descriptive Study I; (iii) Prescriptive study; (iv) Descriptive Study II. Gericke et al. (2022, p. 13) argue that such developed artifacts, i.e., design methods, are constituted by and can be understood from five main elements:

1. The core idea, i.e., "the basic principle, technique or theory that the method employs".
2. The representation, i.e., how information is represented.
3. The procedure, i.e., "the set of actions and activities".
4. The tool, i.e., "an object or artefact that is used to perform some action".
5. The intended use, i.e., "the purpose and scope of a method".

Design method(s) as an umbrella term can thus generally be considered wide in what it covers, where different design methods treat different aspects of design, and apply to different situations and types of products, or artifacts. This thesis, here, argues that the role of any design method is to prescriptively guide designers in generating a set of specific knowledge related to the *design problem* at hand'. This, in turn, supports meeting the overall goal of identifying a good problem-solution fit (Cross, 1992; Ullman, 1992; 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 utilizing the design process paradox (Ullman, 1992) and how design methods (the red rhombs) act as a means of producing knowledge.

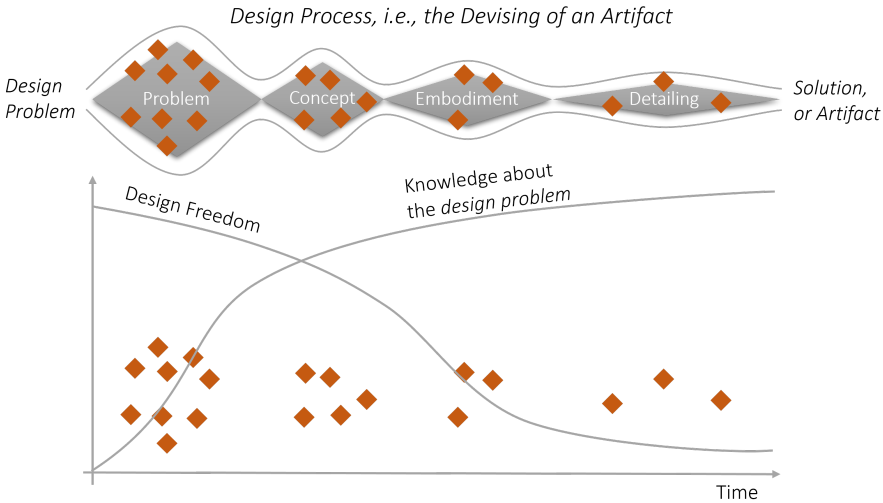

Figure 3.2: A generic design process influenced by Eder (1998) and Pahl et al. (1996) mapped against the design process paradox (Ullman, 1992). Design methods are illustrated as red boxes that support different activities generating knowledge about the *design problem*.

Sustainable design method is a commonly used term in literature when referring to design methods that aim to support the development of more sustainable solutions (see e.g., Faludi et al., 2020). Such design methods, similarly to any design method, focus on generating knowledge about the *design problem*, but more specifically sustainability-related knowledge. *Sustainable design method* is, however, not a term that is used in this thesis. 'Design method focused on sustainability' is instead used to avoid a repetitive separation between 'design method' and 'sustainable design method'.

3.6 Facilitating change of practices

Kotter (1995) proposes one influential but occasionally criticized (see e.g., Appelbaum et al., 2012) model for organizational change, where the following eight steps are explicitly formulated and proposed to facilitate such *change*.

- Establish a sense of urgency about the need to achieve change – people will not change if they cannot see the need to do so.
- Create a guiding coalition – assemble a group with power energy and influence in the organization to lead the change.
- Develop a vision and strategy – create a vision of what the change is about, tell people why the change is needed and how it will be achieved.
- Communicate the change vision – tell people, in every possible way and at every opportunity, about the why, what and how of the changes.
- Empower broad-based action – involve people in the change effort, get people to think about the changes and how to achieve them rather than thinking about why they do not like the changes and how to stop them.
- Generate short-term wins – seeing the changes happening and working and recognizing the work being done by people towards achieving the change is critical.
- Consolidate gains and produce more change – create momentum for change by building on successes in the change, invigorate people through the changes, develop people as change agents.
- Anchor new approaches in the corporate culture – this is critical to long-term success and institutionalizing the changes. Failure to do so may mean that changes achieved through hard work and effort slip away with people's tendency to revert to the old and comfortable ways of doing things.

Kotter (2012, p. 1) elaborates on his eight-step model and argues that the initial reason why *change* fails is due to *complacency*:

> "People don't understand the need for change because they don't see the dangers and opportunities that are ahead. Too often, would-be changemakers don't recognize how their own actions can reinforce the status quo. They underestimate the resources they need to motivate others to leave their comfort zones. And they are paralyzed by the risks that reducing complacency can entail".

Samuelson and Zeckhauser (1988, p. 8) also emphasize that *change* is challenging in their status quo bias in decision making and that it is both easier, and common, to "doing nothing or maintaining one's current or previous decision".

The instant hesitation towards, commonly observed, when proposing design practices via prescriptive design methods can be related to *autonomy* in work. *Autonomy* has previously been highlighted as a key element in successful work design that increases job satisfaction and internal motivation (Hackman & Oldham, 1976)[1]. 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" 1976, p. 258.

The role of *autonomy* has been studied further, and Deci et al. (2017) argue in their *Self-Determination Theory* that basic psychological needs in work design are *autonomy* (but also *competence*, and *relatedness*).

Appropriate consideration of *change* aspects has been claimed to be lacking in sustainable business model innovation literature (Pieroni et al., 2019), a closely related field to sustainable design. Booker (2012, p. 517), for example, claimed that is important to ensure "integration with existing tools to maximize usability and acceptance", and Eder (1998, p. 366) stated that "Some methods fit better with one organization than with another. Each method must be adapted to that organization". These quotes manage to capture the fact that design method adoption, i.e., *change*, both require a process and methodological perspective, but that it is also a challenging organizational, and human-behavioral phenomenon. However, they also symbolize and frame a logical, and pragmatic rhetoric, i.e., they address the phenomenon of *change* by reducing the need for *change*. Furthermore, Quella and Schmidt (2003, p. 113) discussed environmental strategies and that "social acceptance needs to be considered". Faludi et al., (2020) Faludi et al. (2020, p. 4) also stated that "tools should be easier to apply and compatible with existing business and design methods and processes". However, such a mindset and 'pragmatic approach' can also result in stagnation and, instead, limit the ability to propose sustainable solutions. In its extension, failing to appropriately consider *change* as a challenge on its own, simultaneously to the process and methodological considerations, entails a risk to the appropriate adoption of *sustainable design practices.*

Furthermore, Faludi et al. (2020) proposes 'co-creation' to better develop, and propose, design methods for industry focused on sustainability. This proposal does align with e.g., Hackman and Oldham (1976) who argue that practitioner involvement is critical in increasing motivation and acceptance of work practice, and Kotter (1995) who claim that involving people in the process of *change* is key to gain traction. This indicates that the proposal of Faludi et al. (2020) can facilitate adoption, but they do however not refer to

[1]Hackman and Oldham (1976) studied *autonomy* in work design, but in a different context to *sustainable design practices*

any such literature when proposing this. In turn, this highlights the potential of design researchers appropriately considering *change* aspects when developing, and proposing, design methods.

3.7 Human-behavioural considerations in complex decision-making

Much research has focused on proposing theories focusing on the influence of human-behavioral aspects in complex decision-making, or problem-solving activities (read *designing*) in organizations. *Agency theory* (see e.g., Ross, 1973; Mitnick, 1973; Eisenhardt, 1989), for example, has been widely studied but in different research streams using different schools of thought and generally accounts for actions and the relation between actors (i.e., principal-agent) and how it, for example, is influenced by e.g., *bounded rationality*, self-interests, and/or conflicting goals (Eisenhardt, 1989; Mitnick, 1992; Shapiro, 2005). The concept of *Bounded rationality* (Simon, 1969) can briefly be described as humans being biased and unable to make optimal decisions but rather making decisions that are 'satisfactory' due to cognitive barriers i.e., what he refers to as *satisficing*. As a result, humans tend to use *heuristics*, or 'rules of thumb' in 'complex problem-solving activities' (Simon, 1979), i.e., *designing*. Simon (1969, p. 28) elaborates on *heuristics*:

> "Heuristic methods provide an especially powerful problem-solving and decision-making tool for humans who are unassisted by any computer other than their own minds, hence must make radical simplifications to find even approximate solutions".

In this thesis, it is important to acknowledge that some accounts treated in *agency theory* share similar traits to what others have referred to as cognitive barriers or *cognitive biases*, and are of relevance (Mitnick, 1992). Mitnick (2019, p. 4) also explicitly stated, in a non-peer-reviewed paper, that "people make decisions based on things like norms, information with social origins, and what more recent literature terms cognitive heuristics or biases". The presence and influence of norms or informal rules in organizations are further treated in works related to *Institutional theory*, where organizations are seen as part of broader institutional contexts (see e.g., Meyer and Rowan, 1977; DiMaggio and Powell, 1983). DiMaggio and Powell (1983) elaborate on this and introduce the concepts of *institutional rules* and *institutional isomorphic change* which govern how organizations behave or act, and change according to norms and informal rules. These perspectives highlight the evident risks of organizations adopting instances, or 'cherry picking' parts, of *sustainable design practices* due to e.g., *cognitive biases*. Either via the presence of norms, but also as a result of the complexity of sustainability as a 'wicked problem' (Lönngren & Van Poeck, 2021) and expected use of *heuristics*. Additionally, the risks of normalizing such design practices in the manufacturing industry.

3.8 Dynamic capabilities as a mechanism for organizational learning

Dynamic capabilities (Teece et al., 1997) as a term and concept has received a lot of attention in the literature focusing on *change*, and *organizational learning*. Such capabilities broadly relate to an organization's ability to learn and acquire new knowledge and are commonly argued as critical to sustaining competitive advantage and adapting to changes (Eisenhardt & Martin, 2000). The term was introduced and conceptualized by Teece et al. (1997, p. 516) where it is referred to as "the firm's ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments". Zollo and Winter (2002, p. 340) later refine this notion and argue that "a dynamic capability is a learned and stable pattern of collective activity through which the organization systematically generates and modifies its operating routines in pursuit of improved effectiveness". Zollo and Winter (2002) also highlight the knowledge articulation and knowledge codification processes as effective means for building dynamic capabilities as they, for example, can support knowledge diffusion in the organization, and these processes broadly relate to the capturing and explicit making of relevant know-how, or practices. O'Connor (2008, p. 316) instead interprets dynamic capabilities as "process-improvement techniques that constitute the firm's way of modifying operating routines". Dynamic capabilities will not be revisited as such going forward, but it is important to acknowledge its resemblance to how we depict design as a 'knowledge producing process', and design methods as prescriptive knowledge that designers in turn can use to generate new specific knowledge. Furthermore, design and design thinking have previously been framed as a potential enabler in improving an organization's *dynamic capabilities* (see e.g., Magistretti et al., 2021; Sahakian and BenMahmoud Jouini, 2023).

3.9 Facilitating organizational learning using double loop learning

Double loop learning (Argyris, 1977) also relates to the ability to learn, or rather 'unlearn'. *Double loop learning* can briefly be described as the process or feedback loop, where goals and values, along with potential biases or assumptions are challenged in problem-solving or decision-making activities, to better achieve satisfactory outcomes (Argyris, 1977; Argyris, 2002a). Argyris (2002a, p. 1) states that "Double-loop learning occurs when errors are corrected by changing the governing values and then the actions". Argyris (2002b, p. 1) provides a suitable analogy.

> "A thermostat that automatically turns on the heat whenever the temperature in a room drops below 68 degrees is a good example of single-loop learning. A thermostat that could ask, 'Why am I set at 68 degrees?' and then explore whether or not some other

> temperature might more economically achieve the goal of heating the room would be engaging in double-loop learning."

He also elaborates further on effective *double learning* being "a reflection of how they think—that is, the cognitive rules or reasoning they use to design and implement their actions"2002b, p. 1.

Double loop learning is here argued to share a resemblance to how *designing*, or a design process, is depicted in previous sub-sections. *Designing* as a human activity similarly to *double loop learning* strives towards finding a good problem-solution fit, where altering how the *design problem* is framed, or defined, is expected (Archer, 1979; Dorst and Cross, 2001). Liedtka (2015) specifically highlight how design thinking methods, i.e., *designerly ways of knowing*, *thinking*, and *acting* (Cross, 1982; Cross, 2023a) can address such *cognitive biases* (i.e., hypothesis confirmation bias). Furthermore, it is also worth acknowledging that Argyris (1996, p. 396) found an explicit interest in design when he introduced the notion of *Design Causality* and provided his view on design as "specifications of actions to be taken (often in a specified sequence) to achieve intended consequences".

3.10 Previous research on the adoption of design methods and concluding remarks

The adoption of design methods proposed by design researchers has had a low industrial uptake (Karlsson and Luttropp, 2006; Booker, 2012; Gericke et al., 2020; Faludi et al., 2020). Wallace (2011, p. 239) provides a summary of key aspects below.

- Methods tend to be too complex, abstract, and theoretical.
- Too much effort is needed to implement them.
- The immediate benefit is not perceived.
- Methods do not fit the needs of designers and their working practices.
- Little or no training and support are provided by companies.

Eder (1998) emphasizes the need for adapting proposed design methods and adds that practitioners need to claim ownership of design methods and refer to individuals who champion the design method inside an organization. Eder (2009) later refers to method 'experts', which is an individual who has enough experience, competence, and understanding of the design method to ensure it is used as intended, and this is what the study object *method expert* refers to. Jagtap et al. (2014) highlights the need to understand, and incorporate, the fundamentals of *design* in design methods, and that a lack of this can lead to limited adoption.

Previous research provides several relevant insights concerning the challenges of adopting design methods proposed by design researchers in industry, and some of the aspects highlighted in literature are presented in Table 3.1 and Table 3.2. Table 3.1 lists findings from research that studies the adoption of any design method. Table 3.2 instead lists findings from research that studies 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 what the factor is. A non-marked factor indicates that it can either be a barrier or an enabler.

Table 3.1: List of factors, both barriers (B) and enablers (E), influencing the adoption of any design method (Eder, 1998; Araujo et al., 1996; Booker, 2012; López-Mesa and Bylund, 2011). The list provides a sample to illustrate typical aspects touched upon in the literature. 'X' indicates if it is seen as a barrier or an enabler.

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 (Lindahl, 2006; Boks, 2006; Ritzén and Lindahl, 2001). The list provides a sample to illustrate typical aspects touched upon in the literature. 'X' indicates if it is seen as a barrier or an enabler.

Lindahl (2006)	**B**	**E**
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 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

These two lists of factors provide four main insights:

- There are both similarities and differences between the listed factors when comparing the adoption of any design method compared to design methods focused on sustainability.

- The lists are extensive and thus provide a narrow gap for further research on this topic. However, Several of the factors that were identified roughly 20 years ago persist and appear in recent literature, such as the lack of available data, the need for user-friendly tools, and the need for contextual adaptation (see e.g.,Gericke et al., 2020; Gericke et al., 2021; Faludi et al., 2020; Parolin et al., 2024).

- The list of factors is exhaustive and highlights the complexity of the design method adoption.

- The factors also highlight that some of the barriers require further understanding and consideration of organizational, and human-behavioral perspectives to better clarify why these barriers arise.

Furthermore, the manufacturing industry still struggles to appropriately adopt *sustainable design practices* (Vilochani et al., 2024), despite being an attended topic for roughly 20 years (Karlsson & Luttropp, 2006). In summary, this provides a solid foundation for justifying the aim and scope of this research.

Chapter 4

Results

The main results from this research are presented by summarizing the findings from the appended papers. The papers are summarized and each paper's contribution to the thesis and problem is clarified. How the results together support to answer each research question is later done in the Discussion.

4.1 Paper A: Design for Longevity - A Framework to Support the Designing of a Product's Optimal Lifetime

4.1.1 Summary

Paper A identifies and frames the need to actively design products with an optimal lifetime to increase their sustainability performance, which is referred to as *Design for Longevity* in this paper. Furthermore, Paper A also identifies six design strategies proposed in the literature that can be used to prolong the life of products, their components, and materials: (i) Design for attachment and trust; (ii) Design for durability; (iii) Design for standardization and compatibility; (iv) Design for ease of maintenance and repair; (v) Design for adaptability and upgradability; (vi) Design for dis- and reassembly. However, applying and deciding which of these different design strategies to pursue is contextual and requires an understanding of different perspectives when designing for a specific and optimal lifetime. Paper A identifies three perspectives as key to better design for longevity.

- The user's preferences. For example, determine whether the user prioritizes performance over cost, and if users are willing to repair or upgrade the product to prolong the product's life.

- The business perspective, including e.g., how the business makes a profit today and if the business has the capabilities to provide services related to e.g., remanufacturing or upgrading. It can also be that the business need to change to accommodate for the other perspectives.

- The product's lifetime must also be considered from a resource efficiency perspective to ensure the most resource-efficient strategy is targeted. It can for example either be to upgrade the product to enhance its energy efficiency or repurposing the product in a performance-demanding context.

These are considerations that require active attention by designers who aim to design more sustainable solutions with a more optimized product lifetime. Lifecycle thinking is highlighted as crucial when designing products with an optimal lifetime since focusing on specific phases of a product in isolation can lead to sub-optimal performance from a full lifecycle perspective. Designers are thus urged to design "the life of a product" rather than the physical artifact seen in isolation.

4.1.2 Contribution to thesis

Paper A contributes to this thesis by highlighting the complexity of designing more sustainable solutions. The preferred choice of design strategies is contextual and depends on several factors spread across the product's lifecycle. This in turn also requires designers to adopt a lifecycle perspective (i.e., lifecycle thinking) to avoid sub-optimal decisions and introduce further complexity to the design process. This supports answering RQ1.

4.2 Paper B: The Role of the Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing

4.2.1 Summary

Paper B focuses on design methods embodied in computerized tools or software that aim to support designers in designing for additive manufacturing. It also takes a full additive manufacturing value chain perspective, meaning that it goes from a stated need to a physical artifact delivered to the owner of the need, and potential end-of-life activities. Paper B identifies the existing *digital infrastructure* of product development and manufacturing organizations as one barrier to the adoption of design methods, if not considered appropriately during the development of design methods. Furthermore, five key aspects are highlighted related to the *digital infrastructure*.

- Data format incompatibility: Design methods embodied as computerized tools or software make use of different data formats, and the AM value chain typically consists of several computerized tools in a larger *method ecosystem*. A lack of consideration during development can in turn lead to clashes or incompatibility between tools in this ecosystem. This limits the effectiveness and efficiency of the proposed design methods. Effectiveness is reduced if certain results or method outcomes are neglected, and efficiency if instead additional time and resources are added to address potential incompatibilities.

- Information management: Computerized tools or software enable information to be managed completely digitally in the AM value chain and has potential benefits. However, this information needs to be transferred, stored, traced, and retrieved, which in turn needs to be managed appropriately in the AM value chain, and thus also considered during the development of tools.

- Data analysis: The data fed into the computerized embodiment of the design methods typically needs to be 'cleaned' before it can be utilized in the tools or software. This data is typically extracted from other computerized tools or software in the AM value chain. This is in turn not a straightforward plug-and-play activity, and thus also requires consideration during the development of the tools.

- Loss of information: Data is transferred between several tools or software in the additive manufacturing value chain, and there is a risk of losing information in between these steps. This can for example occur when cleaning the data, or when there are incompatibilities that result in the exclusion of critical information, and therefore also require consideration during the development of tools.

- Data and information reuse: Design methods embodied as computerized tools or software result in the ability to reuse data and information to a greater extent in the AM value chain. This provides an opportunity to e.g., generate more knowledge of relevance to better design for additive manufacturing, and should preferably be utilized and thus considered during the development of tools.

Paper B also highlights that there is currently a lack of consideration of these aspects by design researchers in literature. The magnitude when neglecting these aspects during development was further studied using a case study. This study made use of several different computerized tools aimed to support designers in designing for additive manufacturing. This is visualized in Figure 4.1 on the following page. The results from the case study indicate that there is a risk of reducing the effectiveness and efficiency of the proposed design methods if the *digital infrastructure* is neglected. It can for example lead to the need to add time and resources to accommodate the insufficiency of the design methods, but also limit the knowledge that can be generated to support designers to better design for additive manufacturing. The red box in Figure 4.1 highlights where additional resources had to be added to ensure the data could be used. There was also a loss of information in this step due to extensive incompatibility issues.

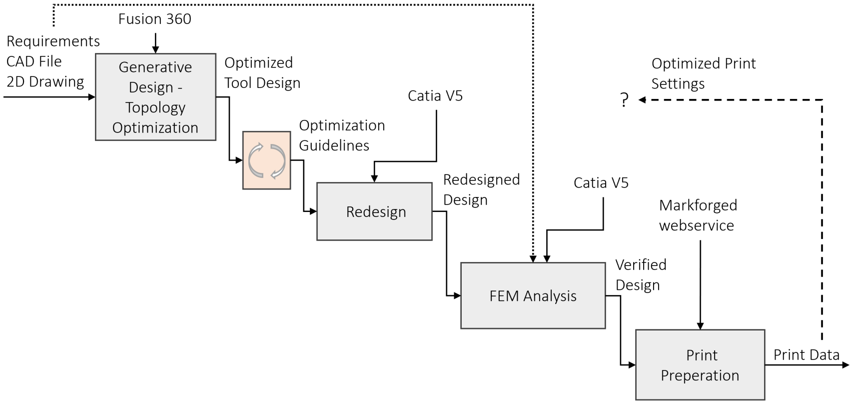

Figure 4.1: Idealised design process (grey boxes) with input/output, and set of utilized tools in the case study. The red box with circled arrows indicates the added step to address the incompatibility.

4.2.2 Contribution to thesis

Paper B contributes to this thesis by highlighting one key facet of the studied topic, i.e., the digital aspects when embodying design methods as computerized tools or software, and supports to answer both RQ1 and RQ3. Further, utilizing advancements in digitalization can both facilitate the adoption of design methods, but also act as a barrier if not considered appropriately during the development. The paper also treats a complete value chain perspective of AM, which adds complexity when developing and proposing design methods. Mainly since accounts for the use of several design methods across the design and realization process of the physical artifact and adopts a lifecycle perspective when designing. This becomes a barrier to adoption due to its complexity, but also a potential enabler that facilitates the adoption when considered appropriately, which provides answers to RQ1 and RQ3.

4.3 Paper C: Derive and Integrate Sustainability Criteria in Design Space Exploration of Additive Manufactured Components

4.3.1 Summary

Paper C focuses on case study A1 in project A where two design methods, developed by design researchers, are used and integrated to enhance the design method outcomes. The case component as such is a Turbine Rear Structure, illustrated in Figure 4.2. The function of this component is to guide turbine gas flow and transfer mechanical load from the shaft to the aircraft mount. The thermomechanical operative, and cyclic, loads limit useful life. So-called off-design loads, such as unbalanced loads in the case of lost fan blade drive design.

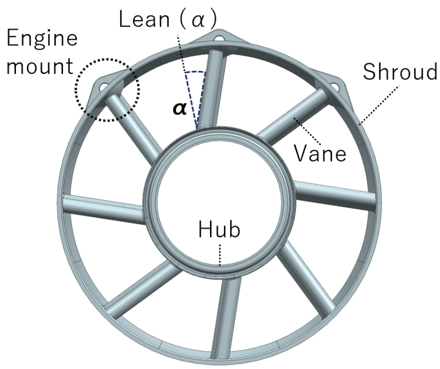

Figure 4.2: A 3D-model of a TRS, seen from the front.

Paper C also made use of a new approach that aims to facilitate the adoption of design methods. It intends to support in identifying what design methods are needed in the current design process to better design more sustainable solutions, and how these can be integrated into the current design process. The results from this approach are presented in Figure 4.3.

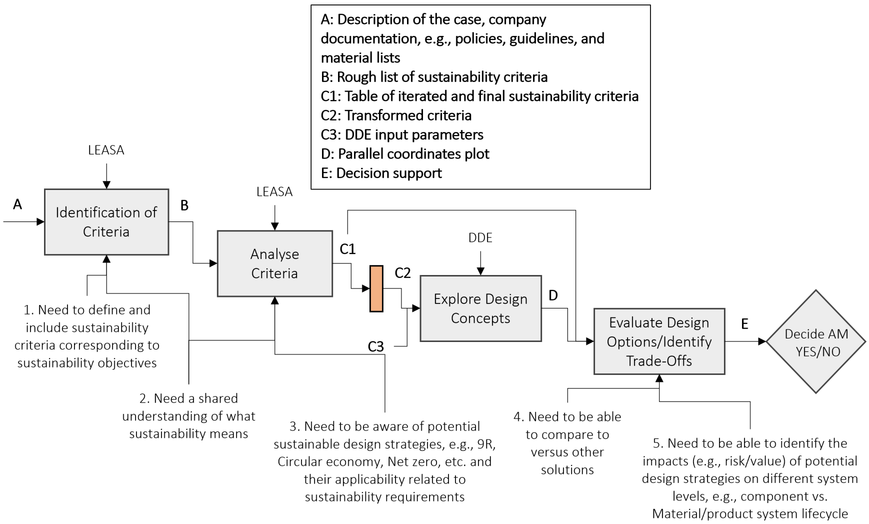

Figure 4.3: Idealised design process (grey boxes) with identified design method needs numbered 1-5. Letters A-E are the in-/outputs. LEASA and DDE are acronyms for the design methods applied. The small red box indicates the added step to address incompatibility.

The first design method used was *Leading sustainability criteria workshop* (LEASA), which is an SPD design method. It was used to identify and formulate *Leading Sustainability Criteria* (Watz & Hallstedt, 2024) from a systems perspective, i.e., social, ecological, and economic dimensions across the product's full lifecycle. The outcome of this design method is a list of sustainability criteria captured in an Excel file as presented in Figure 4.4 on the next page. The criteria as such treat different aspects of the design including both material selection and geometrical parameters, but also the consideration and selection of suppliers as well as activities that focus on e.g., repair or upgrading.

#	Leading Sustainability Criteria (LSC)	LSC Indicator Suggest how to measure compliance to the leading sustainability criteria	Target value (Indicates the desired long-term level of compliance)	Lifecycle phases*					Sustainability dimensions**			Description / Rationale An explanation of the aim with the LSC, describing why it is necessary to address at the earliest stage of product innovation and material selection.
				1	2	3	4	5	Ecological	Social	Economic	
1	Avoid critical materials (alloys, metals and minerals)	Material criticality index score	According to material criticality method	x					x	x	x	Critical includes conflict and risk with virgin materials. Supported by e.g., Code of conduct, product policy/ portfolio plan/ banned substances, requirement from customers.
2	Keep materials in closed-loops	% of material goes to external recycling	0%		x		x	x	x		x	
3	Low Buy to Fly ratio	Bought material (kg)/final product material (kg)	100%		x				x		x	
4	Minimize safety risks: Avoid hazardous materials and accidents	Accidents, death, illness	0%	x	x		x	x		x		Mainly social and economic dimension covered but also ecological dimension affected (less hazardous materials).
5	Avoid a mixture of different types of materials	One pure material	100%	x	x				x		x	Pure material has a value in the end of life and do not require extra treatment.
6	Resource efficient repair	Resource cost of repair in relation to repair hours - as efficient as possible	100%					x	x		x	Resources are: energy, water, material, etc. Less virgin material means less impact .
7	Safe repair	Accidents, death, illness	0%				x	x		x		No risk of accidents during repair, Safe operation after repair.
8	Keep components in closed-loops	% of components going to repair, refurbishness, or remanufacturing	100%				x	x	x	x	x	Less virgin material means less impact.
9	Minimize weight	kg	as low as possible			x		x	x		x	Low weight is reducing fuels both during use and transportation.

*Lifecycle phases:
1. Raw materials, 2: Manufacturing, 3: Packaging and Distribution, 4: Use and Maintenance, 5: Upgrading and/or End of Life

**Sustainability dimensions:
Ecological; Social; Economic

Figure 4.4: *Leading sustainability criteria* for the TRS.

These criteria were later integrated into another design method, a computerized SED design method. This design method uses *digital design experiments* (DDE), see e.g., Martinsson Bonde et al., 2022, to explore alternative solutions using a set of predefined geometrical and material parameters in the early design phases. This integration was not straightforward and required added resources and time. There were also some incompatibilities between the two design methods, but ultimately made it possible to jointly assess some of the *leading sustainability criteria* with existing product criteria focusing on e.g., mass, and max deformation. The results are presented using a parallel coordinates plot in Figure 4.5, illustrating how different designs perform with respect to the criteria.

4.3.2 Contribution to thesis

Paper C highlights the potential of, and supports the integration of sustainability in the design process by using a combination of design methods. However, Paper C also highlights that integrating different design methods is not straightforward as it requires an additional step that is both time-consuming and complex. This supports answering both RQ1 and RQ2 respectively.

There were also parts of the output from LEASA that were not integrated appropriately into the analysis, i.e., an incompatibility, and thus also into the design process. This more specifically related to sustainability criteria that did not concern either material selection and/or geometrical aspects, was were difficult to incorporate and assess in the DDE. The sustainability criteria also introduced lifecycle thinking in the design process, which challenged the current ways of working. Furthermore, several of the sustainability criteria, including material selection and geometrical aspects, were also difficult to incorporate and assess due to a lack of valid information and data. This in turn highlights that there is currently a risk of only considering a partial spectrum of the sustainability criteria that preferably should be assessed concurrently. This supports to answer RQ1.

Paper C also highlights that integrating more than one design method into the existing design process is complex. It requires consideration of both the *digital infrastructure* and the existing *method ecosystem* as such. The new approach that was used to identify how design methods can be integrated into the current design process did support this in two ways. (i) The approach supported in highlighting what design methods are needed in the process. (ii) The approach also supported highlighting where and how the design methods fit. This in turn clarifies what potential adaptations of the design methods are required to better fit the current design process. This supports to answer RQ3.

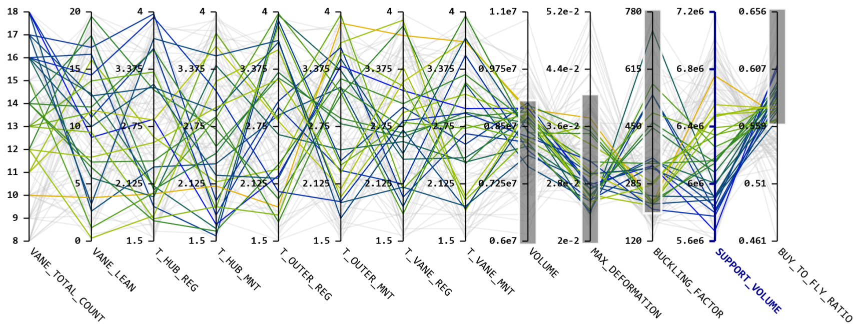

Figure 4.5: Parallel coordinates plot depicting the inputs and outputs of the digital experiments

4.4 Paper D: Sustainability Criteria for Introducing New Technologies in Low-Income Contexts

4.4.1 Summary

Paper D focuses on the SPD design method *Sustainability Fingerprint* (Hallstedt et al., 2023b) along with how it was proposed and adapted to fit the needs of Engineers Without Borders Sweden (EWB-SWE). This design method consists of a sustainability profile, i.e., a set of several *leading sustainability criteria*

(Watz & Hallstedt, 2024), and adopts a systems perspective on sustainability. The *Sustainability Fingerprint* also utilizes *Sustainability Compliance Indices* (Hallstedt, 2017) to further break down the *leading sustainability criteria* into more concrete and quantifiable metrics. This sustainability profile is also embodied in a matrix-like tool in Excel, and an appropriately proposed *Sustainability Fingerprint* makes it possible to:

1. Guide designers towards a more sustainable design.
2. Compare alternative designs.
3. Assess the sustainability performance of a design.

A *Sustainability Fingerprint* is also to some extent contextual and can differ from company to company, and/or product to product. The *Sustainability Fingerprint* proposed to EWB-SWE was therefore adapted to fit the context of humanitarian engineering NGOs[1] that introduce new technologies in low-income contexts.

This entailed some differences in how the tool was developed and adapted, compared to how Hallstedt et al. (2023b) originally proposed. (i) Instead of a multidisciplinary team of experts, were a combination of a literature review, interviews with experts at EWB-SWE, and researchers in sustainable design, used to identify the *leading sustainability criteria*. (ii) The first version of the *Sustainability Fingerprint* also required major modifications and adaptations, or simplifications, to fit the needs of the volunteers. The requested modification was to remove the *Sustainability Compliance Indices* as it was considered to require a more thorough assessment, which makes the use of the design method too time-consuming and cumbersome. This in turn resulted in one single qualitative scale for each criterion, and the proposed *Sustainability Fingerprint* was therefore classified as a *Simplified Sustainability Fingerprint*.

The final *Simplified Sustainability Fingerprint* is presented in Figure 4.6 embodied in an Excel. Each of the identified *leading sustainability criteria* is placed in their corresponding lifecycle phase and provided with a brief explanation, rationale, and indicator. Excel was used to enable a more intuitive structure that depicts the criteria for each lifecycle phase, with additional text boxes for comments on 'how well a criterion is met', and 'actions for improvement'. This aims to improve e.g., scalability and communication of the design method.

[1] Non-Governmental Organizations

Simplified Sustainability Fingerprint Tool EWB-SWE
Developed by: Amanda Jonasson & Sara Petersson 2023

Project:	
Concept Name:	
Assessed by:	

Guide:
1. Read through the sustainability criteria, and use the explanation of each criterion to understand how it can be measured/assessed on the defined indication. It explains what each criterion is and why it is important to use.

2. Once a minimum of one concept or solution have been developed, this tool is used to assess the sustainability profile of the solution. It can be used as an analysis tool to raise awareness on what sustainability aspects are important to consider when developing a solution in the Humanitarian Engineering context.

3. Based on your developed concept or solution, go through each criterion and comment on how the solution fulfills or not fulfills the criteria as well as state potential actions to take in order to improve the sustainability indication.

For more information about a Sustainability Fingerprint Tool read the related article:
Hallstedt, S., Villamil Velasquez, C., Lövdahl, J., & Nylander, J. W. (2023). Sustainability Fingerprint - guiding companies in anticipating the sustainability direction in early design. Sustainable Production and Consumption, 37, 424–442. https://doi.org/10.1016/j.spc.2023.03.015

For more information about how this Template was developed read:
A Feasibility Study Process for Humanitarian Engineering, Increasing the Social Impact for a Swedish NGO. Master Thesis by Amanda Jonasson & Sara Petersson, 2023.

Life-cycle phase	**Materials acquisition**		**Implementation of solution**		**Usage & maintenance**									**Solution end-of-life procedure**	
Criteria	**Local Materials & Components**	**Renewable Materials**	**Equal/equitable Suppliers**	**Community Engagement**	**Solution Affordability**	**Solution Desirability**	**Solution Accessibility**	**Solution Safety & Health Risks**	**Environmental Risks**	**Increased opportunity for Jobs**	**Increased opportunity for Education**	**Equality Promotion**	**Responsible & Renewable Energy Sources**	**Available materials & components**	**End-of-life Procedures**
Explanation of Criteria	Local materials and components are obtained from a defined radius around the project site, which helps to support the local economy and reduce transportation costs and energy consumption in the community.	Renewable material's rate of growth is not larger than their rate of use, their environmental impact is lower than non-renewable materials and their availability is not threatened by their use. Examples are bamboo, wood, cork etc. Recycled materials are measured as the total percentage of recovered materials in a product.	Equal and equitable suppliers refer to, the extent that the suppliers are working towards equality and inclusivity within the workspace. When marginalized groups are empowered and included in decision-making processes, they can contribute with their unique perspectives and knowledge to create more effective and sustainable solutions.	Community engagement helps the implementation of a solution that is culturally appropriate, effective, and sustainable. The project team builds relationships, understands cultural context, and enables co-creations by arranging workshops and seeking continuous feedback.	Solution affordability is to what extent the solution is affordable compared to people's average income in the area. An affordable solution should not compromise its quality or sustainability aspects. If a solution is not affordable to everyone it might not help those who need it the most.	Solution desirability is the degree to which a proposed solution is attractive, acceptable, and feasible to stakeholders. Desirable solutions tend to be more long-term socially sustainable and it ensures a solution that the locals will be proud of.	Solution accessibility is the extent to which the solution is inclusive, equitable, and user-friendly for the intended users. Minority group characteristics could be race, ethnicity, religion, gender identity, sexual orientation, age, and disability. Ensuring an accessible solution helps to bridge the gap in the community for minorities.	The solution should not put the user's safety or health at risk during maintenance and usage to ensure that it's not harmful to anyone. Examples of risks include: Physical injury or harm to the user electrical hazards or exposure to hazardous substances. A safe work environment lays the basis for a successful solution.	Environmental risks refer to the extent to which the solution causes extensive pollution and waste production during use. Examples could be high green house gas (GHG) emissions from heating schools, or high generation of non-biodegradable waste with no waste treatment system. To not further negatively affect the environment in the region.	Increased opportunities for jobs in the local community help to tackle unemployment and reduce poverty. By building local community capacity, engineers can design and implement solutions that are culturally appropriate, economically sustainable, and community-owned.	Increased opportunities for education and knowledge creation create new opportunities for individuals and communities. Acquiring new skills and knowledge can create new economic opportunities and contribute to the development of local communities.	Promoting equality helps to create a more sustainable and resilient society. A solution should empower and strengthen women and other minority groups' rights in the community. For example, it can be to provide education for persons with disabilities and to include economic mechanisms that create entrepreneurship opportunities for women.	Sustainable renewable energy sources such as solar, wind, hydroelectric, geothermal, and biomass can be replenished or renewed over time but they must also be environmentally and socially responsible. Not all renewable sources are responsible for example if wildlife, forests, etc. are negatively affected.	Available materials and components are not threatened by their use. Long-term available components and materials are especially important for critical components of the solution and the availability of spare parts. Otherwise, it can negatively affect the long-term use of the solution.	The end-of-life procedures refer to the extent to which the solution produces waste and GHG emissions during end-of-life procedures., and to what extent it is part of a circular economy (this involves a sustainable take-back system). Not considering this increases the chances of it not being safely or sustainably taken care of.
Indication	The solution maximises the use of locally sourced and produced materials and components.	The solution maximises the use of renewable or recycled materials (recycled materials can be non-renewable).	The solution maximises the use of suppliers that promotes and are actively working towards equality and inclusivity with 50/50% of women and men in their workforce.	The solution maximises community engagement during the EWB project process, implementation, and use stages.	The solution maximizes affordability for the intended users in the local community.	The solution addresses all of the identified needs, aspirations, and expectations of the intended users in the local community.	The solution maximises & promotes accessibility for the intended users in the community.	The solution minimises the risks posed to the user's health and safety.	The solution minimises GHG emissions during use and the waste is part of a circular economy.	The solution maximises the amount of job opportunities for the local community.	The solution maximises the opportunity to provide training, education and knowledge sharing in the local community.	The solution actively works towards achieving gender equality.	The solution maximises the use of energy from responsible and renewable sources throughout the whole lifecycle.	The solution maximises the acquisition of materials and components that are long-term available.	The solution is part of a circular economy where the number of components and materials that are reused and reproduced is maximised.
Comment How well does your solution fulfill these criteria?															
Actions to be taken															

Figure 4.6: Snapshot of the final *Simplified Sustainability Fingerprint* proposed to EWB-SWE. Retrieved from (Jonasson & Pettersson, 2023).

The proposed design method was also evaluated by practitioners inside EWB-SWE, and it was considered to be useful in three ways: (i) To score the sustainability performance of different designs; (ii) As a means to raise awareness of important aspects that need to be considered; (iii) To aid in decision making. There was also a consensus that the use and application of the tool depend on other activities, or design methods, in the design process. The outcomes of these activities provide additional information and knowledge required to appropriately assess the sustainability criteria.

Paper D also assesses aspects related to the applicability and use of the proposed design method concerning how EWB-SWE's current design practices.

- Humanitarian engineering NGOs need to utilize a design process that is supported by several design methods and tools that ensure the sustainability criteria can be assessed appropriately as well as fulfilled.

- The sustainability criteria cover several interdisciplinary aspects, and NGOs need to ensure that project teams have a wide competence set, including e.g., both technical, social science, and entrepreneurial competencies. The proposed sustainability criteria as such also put further emphasis on closer collaboration between NGOs and their local partners, and suppliers.

- Humanitarian engineering NGOs need to strive towards creating long-term collaborations with local partners that are willing to have a long-term strategic approach to ensure the sustainability criteria are met over time. NGOs need to be more selective when choosing what local partners they should collaborate with, such that they align with internal ambitions and targets.

- Humanitarian engineering NGOs should strive to design similar and/or niche projects and solutions. Solutions can in such cases be reused and support improving the sustainability performance of their projects or solutions each time they are carried out, and potentially improve implemented projects over time.

4.4.2 Contribution to thesis

Paper D highlights the importance of involving the practitioners, and adapting the design method to fit their and the organization's needs to increase the chances of adoption, which supports answering RQ3. Furthermore, several of the criteria require EWB-SWE to change their current design practices, which supports answering RQ1.

Paper D also highlights the importance of considering a larger *method ecosystem* perspective, as the practitioners inside EWB-SWE acknowledged that the use of this proposed design method is dependent on the information from other design methods, or activities. It is therefore important to understand when and where in the design process the design method fits, and how it influences its use. This in turn supports answering RQ3.

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

4.5.1 Summary

Paper E focuses on the collected data from Project A, where multiple case studies (A1-C3) across three different product development and manufacturing organizations were the main sources. These case studies involved 30 workshops, four seminars, and more than 20 informal interviews leading to a large sample of qualitative empirical data. This data was analyzed using *Glaserian Grounded Theory* and resulted in a descriptive framework that captures 53 interdisciplinary factors influencing the adoption of *sustainable design practices* using new and improved design methods. These factors relate to eight different *core categories*.

- **Category A - Practitioners' understanding of why and how to use design methods:** It relates to practitioners' 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 practitioner 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 practitioners, 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 practitioners' 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 practitioners and the new design methods proposed by *method experts* and/or *developers*.

The descriptive framework is presented in Figure 4.7[2] where a network diagram is used to illustrate the interdependent factors acting either as 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 4.7 using a directed arrow with text centered on the line to briefly describe the factor. All positive influences, i.e., the enablers, are blue with a plus sign next to the arrow. All negative influences, i.e., the barriers, are red with a minus sign next to the arrow. Moreover, the framework also captures and displays factors that indirectly influence the center circle, which occurs when there are factors between categories that result in second and/or third-order effects.

The complete results from the theoretical coding are provided in Paper E and provide a detailed analysis of all 53 factors in a structured manner category by category, as follows:

1. The factor is presented and indicates if it has a positive ('enabler') or negative ('barrier') influence and which category it influences.

2. The factor's occurrence is also qualitatively denoted as either 'occasional', 'frequent', or 'constant'.

3. The factor is clarified along with its consequence.

Paper E identified three enablers in the descriptive framework that are worth highlighting.

[2]The descriptive framework is exhaustive and the reader is therefore urged to digest it lightly here since key aspects will be highlighted in the coming parts of the thesis.

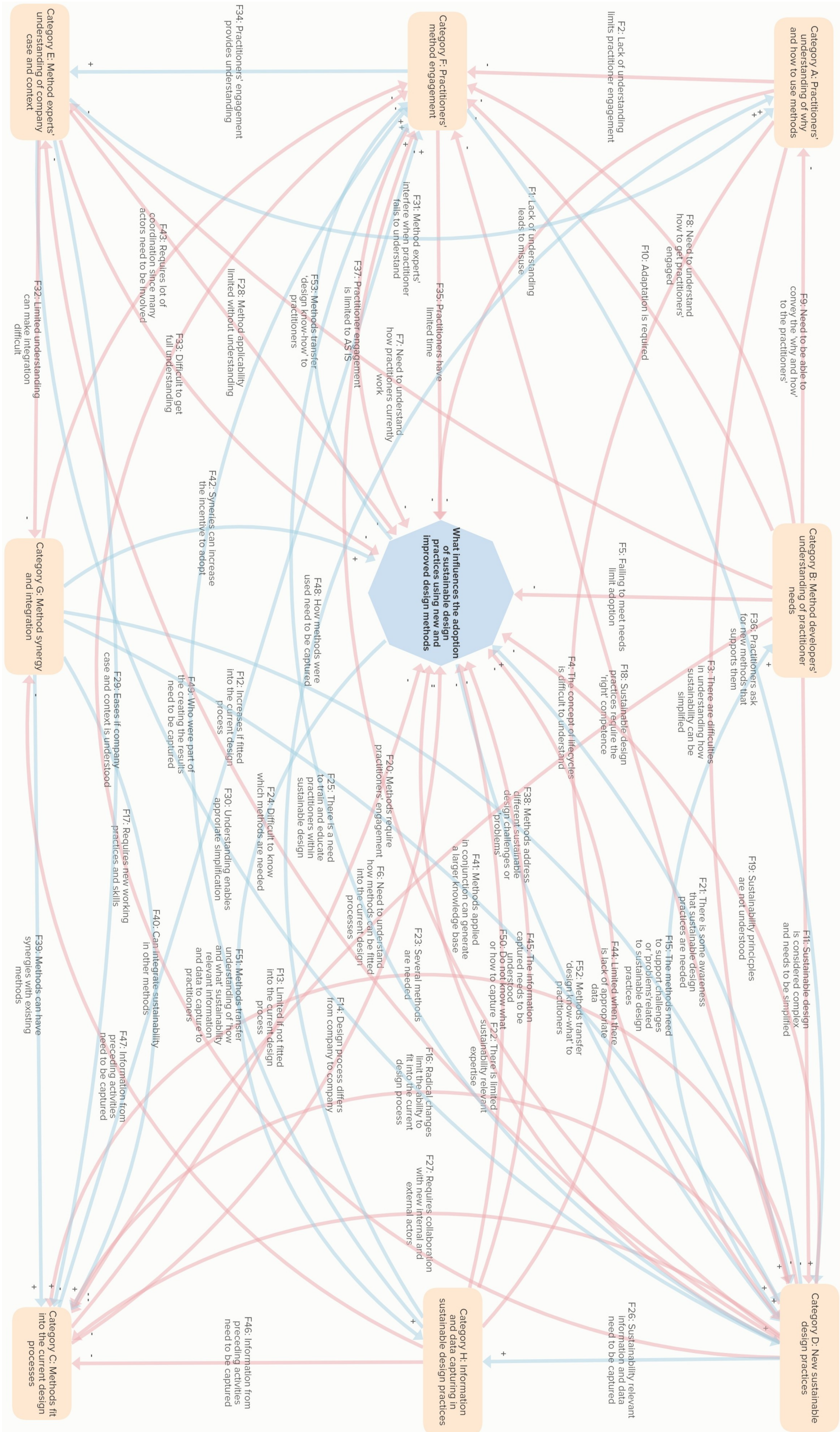

Figure 4.7: The final descriptive framework of the 53 interdisciplinary factors influencing the adoption of *sustainable design practices* using new and improved design methods. “Design methods” is shortened to “method” in the figure.

Factor 51 - design methods transfer understanding of 'how and what' sustainability relevant information and data to capture to practitioners. The design methods had a prescribed input along with how information and data should be represented, this was observed as supporting practitioners to create a common language and representation of sustainability information and data. One practitioner did, for example, state that the design methods *"provide a common language and shared understanding of sustainability"* as well as *"terminology around sustainability"*. Furthermore, the design methods also prescribe what sustainability information and data is needed to appropriately use the design methods, i.e., relevant sustainability data. This clarified what information and data is necessary to retrieve and store both from internal functions and external stakeholders, such as suppliers. One practitioner did for example state that *"the method resulted in a way to express component requirements to suppliers"*. Another practitioner 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. It more specifically increased their awareness and understanding, i.e., knowledge, of what change of and/or new design practices are needed to transform to *sustainable design practices*. It highlighted what sustainability-related 'problems' need to be addressed and/or what knowledge is relevant to produce that in turn can be used to increase the sustainability performance of their solutions. One practitioner did for example state that the main purpose of the design methods is to *"ask the right questions"*, i.e., what 'problems' to solve or knowledge to produce. It was occasionally observed as also transferring the ownership of these 'problems' to the practitioners. Furthermore, practitioners had their presumptions about what sustainable design or *sustainable design practices* imply or mean, and what 'problems', or knowledge is relevant to their company. Adopting the design methods challenged these presumptions and supported them in clarifying what knowledge is relevant, and what sustainability-related 'problems' need to be solved. The practitioners themselves also frequently claimed to obtain increased awareness and understanding of what change of design practice is needed by adopting the design methods. One practitioner did, for example, state that *"I have learned so much more, I thought I already knew a lot"*. Another practitioner 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. It more specifically increased their awareness and understanding i.e., knowledge, of how their current design practices can be changed, and ideally should be changed. It highlighted how to solve their sustainability-related 'problems' and/or how to produce relevant knowledge that in turn can be used to increase the sustainability performance of their solutions. The design methods prescribe who needs to be involved and how they should be involved in the design methods. Furthermore, the design methods also prescribed a structured approach for what questions need to be answered as well as what actions and inputs are needed to reach specific outcomes, i.e., how to produce knowledge or how to solve a ‘problem’. It was constantly observed that this supported practitioners in better understanding of what actions and by whom are required to reach specific outcomes, i.e., how to adopt *sustainable design practices.* One practitioner did for example state that the design methods support in a *“structured way of how we can achieve the sustainability goals – where to start and then which actions to take”.* Another practitioner stated that it *“provides a structured way of integrating sustainability”.*

Two new concepts were also proposed in Paper E to conceptualize the nature of design methods, which is based on the empirical findings. From a practitioner’s point of view, design methods support solving their ‘problems’. These ‘problems’ are situational problems or challenges, and occasionally explicit and unmet needs that arise in the design process when current design practices, or design 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 practitioner. *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 practitioners 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 from organization to organization, or from case to case and are thus contextual. Examples of *contextual problems* were requests to adapt the design methods to company language, or what some practitioners referred to as making them “companyfied” and thus differ from organization to organization. Another *contextual problem* instead related to the need to efficiently link the design methods, or rather their accompanied computer tools, to the organization’s internal information and data management system. Such systems also differed from organization to organization and became a *contextual problem.* In many instances, *contextual problems* were generally related to explicit requests to simplify, adjust, and/or modify the design methods to better align with their organizational context (e.g., product, internal processes, and resources).

The *dualism of design methods* builds on the finding that factors 52 and 53, where design methods were observed to transfer both ‘design know-what’ and ‘design know-how’ to practitioners. The *Design know-what* encapsulates and transfers knowledge of what *situational design problems*, *situational sub-problems*, and occasionally *contextual problems*, are relevant to practitioners, i.e., what knowledge needs to be generated, and what problems need to be solved to appropriately adopt *sustainable design practices*. The *Design know-how* instead encapsulates and transfers knowledge of how practitioners can solve specific *situational design problems*, *situational sub-problems*, and occasionally *contextual problems*, i.e., how knowledge can be generated, and how problems can be solved to appropriately adopt *sustainable design practices*. Furthermore, this highlighted that design methods are constituted by two halves, or a 'dualism', captured in Figure 4.8. The *Double Diamond* (Design Council, 2005) was used for pedagogic reasons to highlight this dual nature and frame design methods as designed artifacts (i.e., designs). The generic steps of the DRM (Blessing and Chakrabarti, 2009) were also fitted accordingly as it is commonly used when developing design methods.

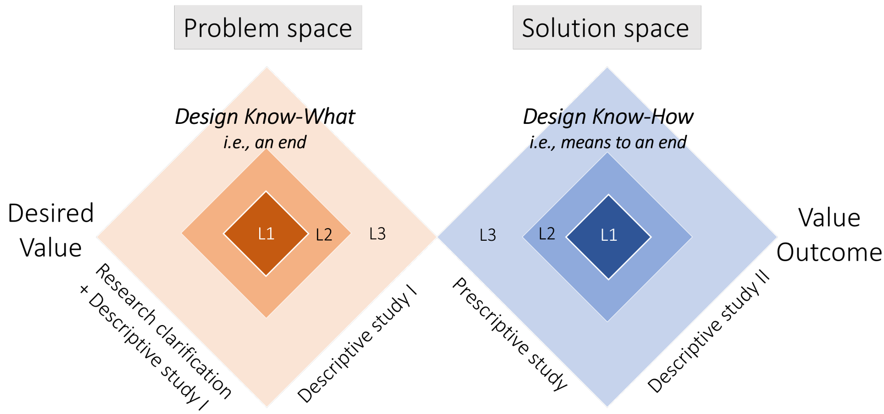

Figure 4.8: Illustration of the *dualism of design methods* where design methods are divided into the *Design know-what* as a 'problem space' and the *Design know-how* as a 'solution space'. This is further divided into the *Situational design problem* (L1), *Situational sub-problems* (L2), and *Contextual problems* (L3).

This supported highlighting that design methods are value-laden artifacts, or *designs* i.e., means to an end, where the end is value-laden. The descriptive framework was also compared to literature in Paper E both to refine but also to strengthen the empirical findings. This procedure is provided in Paper E and resulted in nine *systemic barriers* and seven propositions, which are presented in Table 4.1 and Table 4.2. The tables capture and consider the three perspectives to different extents clarified with an "X". Furthermore, the *systemic barriers* are of a systemic nature which summarizes and highlights key barriers. The propositions are instead suggested actions, for addressing these *systemic barriers*. Table 4.1 focuses on findings that were more generalizable for the adoption of any design methods. Table 4.2 (on page 56) instead focuses on findings that were specific to the context of design methods focused on sustainability.

Table 4.1: *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

4.5.2 Contribution to thesis

Paper E supports answering all RQs. The descriptive framework provided in Paper E frames 53 barriers and enablers to the adoption of *sustainable design practices* using new and improved design methods. The descriptive framework provides detailed answers to RQ1 but also RQ2, and RQ3. Furthermore, the proposed concepts the *situational design problem* and the *dualism of design methods* in Paper E together support answering RQ2. That is, by expanding the role of new and improved design methods in a *sustainability transformation*, and that they can be used to convey and/or transfer:

1. How to solve *situational design problems* relevant to the *design problem*.

2. What *situational design problems* are relevant to the *design problem*.

And, they can be used to convey and/or transfer:

3. How to produce knowledge relevant to the *design problem*.

4. What knowledge about the *design problem* is relevant to produce.

This model was also to facilitate the comparison between the descriptive framework and the literature. In turn, this supports answering both RQ1, RQ2, and RQ3 via the *systemic barriers* and *propositions* presented in Table 4.1 and Table 4.2.

Table 4.2: *Systemic barriers* and *propositions* specific for the process and methodological context of *sustainable design practices*. 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	

Chapter 5

Discussion

This chapter discusses the joint results of this research and how it supports to answer the research questions. The answers to each RQ are discussed in Sections 5.1, 5.2, and 5.3 below based on the findings of this research. This is followed by discussing their validity in Section 5.4. The findings presented in this thesis do address all RQs, but establishing an answer to RQ1 and RQ2 has been the main focus of this research until now. There are answers to RQ3 but these require further research going forward, and will be further clarified below and in Section 6. This was clarified in the Research Approach using the DRM to visualize how the focus of this thesis lies on Descriptive Study I, and future work will instead focus on the Prescriptive Study and Descriptive Study II.

5.1 Barriers to the adoption of sustainable design practices using design methods

The descriptive framework illustrated in Figure 4.7 provides answers to RQ1 but the framework is cumbersome. This is mainly because the factors are interdependent, and addressing one of the 53 factors does not necessarily 'solve' the underlying problem of the studied topic. Instead, the framework needs to be treated on a more holistic level that addresses key problems, or what was framed as *systemic barriers* in Paper E. Furthermore, utilizing the collective results from all appended papers it is possible to group and summarize the answers to RQ1 as **five key barriers**. These five key barriers will be discussed in the coming sub-sections.

5.1.1 Prescriptive design methods and the influence of human-behavioral aspects

Paper E, together with the previous literature, frame design methods as prescriptive which in turn conflicts with human-behavioural needs. This is one key problem with the adoption of design methods, it is 'human' to resist adoption. This has been further studied in previous research, whereas it is framed as *autonomy* in work design (Deci et al., 2017; Hackman and Oldham, 1976). This is also related to what Kotter (1995) argues in his model for facilitating change, where involving people in the process of change is highlighted as crucial. Expanding on this, if a design researcher, or *method expert*, simply proposes a prescriptive design method that a practitioner should 'blindly adopt', there is limited room for such involvement. It is therefore in turn, expected that the adoption of prescriptive design methods is low, if not facilitated appropriately.

The complexity, or challenge, of this notion is further emphasized with the proposal of the *dualism of design method paradox* provided in Paper E. This paradox argues that it is only possible to see the value, or have the intrinsic need, for adopting a design method once it is adopted. This is partly supported by previous literature that similarly highlights that practitioners rarely are aware of the value a design method provides (see e.g., López-Mesa and Bylund, 2011). Kotter (1995) also argues that it is important that there is a "sense of urgency" before change can gain traction, which also supports highlighting why there must be an intrinsic need for adopting design methods before adoption is possible. Furthermore, López-Mesa and Bylund (2011, p. 19) also acknowledge that "people do not want to change their way of working". This thesis supports with some clarity why this is, in the concept of *dualism of design method*. This concept argues that design methods are value-laden artifacts, and the value must be adopted —but seldom is. This way of reasoning is illustrated in Figure 5.1, which figuratively highlights how a non-facilitated approach leads to a 'non-functioning system' compared to a 'functioning system' with a facilitated approach.

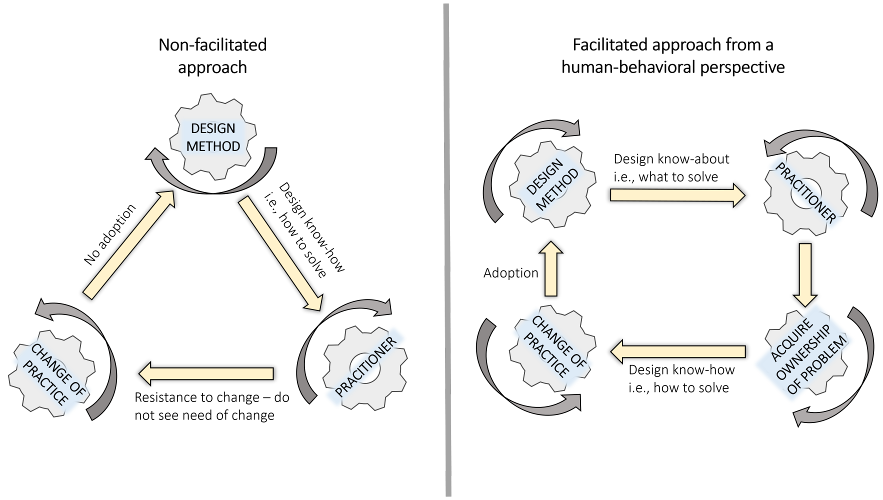

Figure 5.1: Non-facilitated versus facilitated approach and how it leads to successful adoption of a design method.

The proposed concept in the *situational design problem* in Paper E also provides further nuances to this reasoning. This concept highlighted that design methods occasionally treat 'problems' that are of no relevance to practitioners, and they therefore see no intrinsic need to adopt the design method. This in turn, also means that it is not necessarily the design method as a 'design' that is the reason for low adoption, but the 'problem', i.e., *situational design problem*, it solves.

5.1.2 The contextual complexity of design method adoption

Papers A, B, C, D, and E all highlight the contextual complexity of adopting design methods, which in neither of the cases was a 'plug-and-play' activity, and Paper E frames this as the *situational design problem paradox*. This paradox claims that design methods, in theory, are limited in their transferability, or applicability, since *situational design problems* 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 every time, and always require some adaptation. Such adaptation, in turn, becomes a challenge since: (i) it requires domain-specific knowledge but (ii) also the involvement of a *method expert*, and (iii) the occasional need to solve *contextual problems*. Eder (1998, p. 368) also 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*.

This is a key barrier since neither the domain-specific competence nor design method expertise required to do such adaptation is obtained easily. In its extension, this either puts demands on the: a) design researchers, or *method experts*, with expertise in how to appropriately adapt the design method, who then need to acquire sufficient domain-specific knowledge that requires extensive efforts. This in turn potentially limits the possibility of scaling a design method since one or a few persons need to be utilized recurrently; b) Practitioner with sufficient domain-specific competence, who then needs to acquire the expertise and competence required to appropriately adapt and solve *contextual problems*. This, in turn, requires appropriate supplementary material such as templates, guides, educational material, consideration of the *digital infrastructure*, and potential guidance from another *method expert*.

Furthermore, adoption did in all cases require adaptations, and occasional development and refinement efforts to meet the expected demands and needs of the organizations and their practitioners. Different *contextual problems* appeared in all the appended Papers, either related to the organizations as such, i.e., current process, company language, and the existing *digital infrastructure*, and some were also product-specific adaptations. It was also occasionally stated by practitioners that the proposed design methods need to be embodied in more user-friendly computerized tools. However, such 'problems', or barriers, are at the same time contextual and it is questionable if they can be considered as a scientific activity. The results (i.e., problems and solutions) of these activities will be difficult to generalize beyond that context, hence the name used to frame these (*contextual problems*). Wallace (2011) also highlighted this dilemma while also adding that it is not necessarily the case that the design researcher even has the appropriate skills to meet the demands of modern organizations.

5.1.3 The paradigm of product design in the wake of sustainable design

Papers A, C, D, and E all highlight the need for lifecycle thinking and a systemic approach to sustainability when the goal is to design more sustainable solutions. However, Papers C, D, and E all find that this is not how *design* is currently practiced and/or perceived by practitioners. Paper E frames this as a *paradigm of product design* that persists in the manufacturing industry, and possibly other industries, which takes support from several sources (see e.g., Cross, 2023a; Lee, 2021; Ulrich and Eppinger, 2016). Such a paradigm treats and practices *design* with a strong focus on functionality and performance in use (e.g., weight, power), geometry, component, and part integration, along with material selection. This is a key barrier since such a paradigm currently inhibits some of the key facets of *sustainable design practices* from being adopted, i.e., lifecycle thinking including a systemic approach.

This paradigm is incompatible with *sustainable design practices* from a process and methodological perspective, and there is low social acceptance when such process and methodological conflicts occur. In turn, practitioners frequently request adaptations and modifications, or 'improvements', i.e., simplifications, and use of *heuristics* (Simon, 1969), to accommodate for this paradigm leading to inappropriate adoption of *sustainable design practices*. For example, excluding the value chain perspective, and/or neglecting the social dimension to a large extent. Failing to accommodate such requests occasionally leads to the rejection of the proposed design methods (or their outcomes). One recurring aspect that was mentioned by practitioners frequently is the time and complexity required to adopt the design methods. This can in turn lead to inappropriate simplifications, or *heuristics*.

A potential *paradigm of sustainable design* does however acknowledge and highlight the extent of change needed (Bocken et al., 2014; Ceschin and Gaziulusoy, 2019; Hallstedt et al., 2020). This thus becomes a key barrier to the adoption of *sustainable design practices*, and design methods incorporating the principles of the *FSSD*. Furthermore, a shift from the *paradigm of product design* to a *paradigm of sustainable design* needs further, and appropriate, consideration of human-behavioral and organizational aspects. Such a shift, or *sustainability transformation*, requires expertise and competence beyond what a design researcher, or *method expert* possess, who instead have a process and methodological expertise of what type of change is required.

5.1.4 The presence of cognitive biases and the risk of pseudo-sustainability

The presence of *cognitive bias* appears explicitly in Paper E where it is framed as one key barrier to the adoption of *sustainable design practices* using design methods. The current presumptions of sustainability inhibit practitioners from having an intrinsic need to adopt design methods focused on sustainability. Such *cognitive biases* support the *paradigm of product design* to persist, which in turn entails the risk of organizations to develop *pseudo-sustainable designs*[1]. Figure 5.2 provides a figurative example of how *cognitive biases* can result in a reduced scope in comparison to a systemic approach to sustainability.

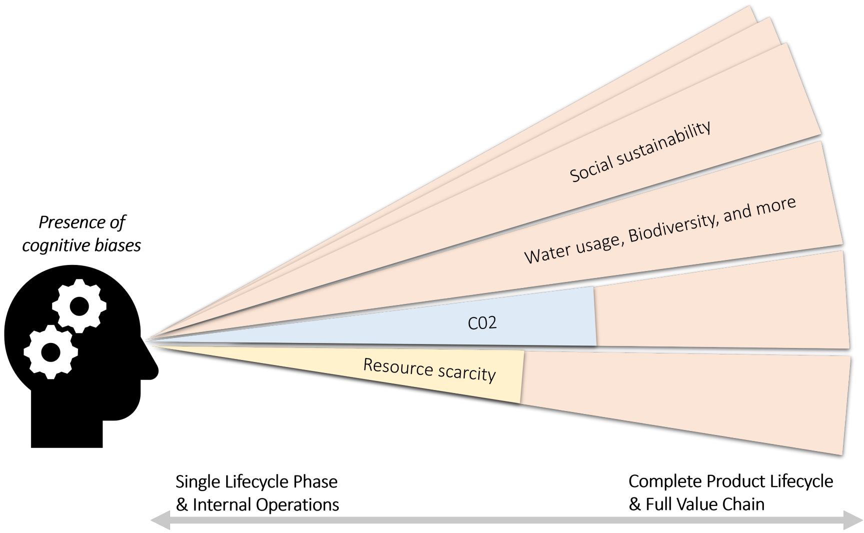

Figure 5.2: Figurative example of how *cognitive biases* influence how sustainability is perceived and treated.

Simon (1969) provides clarification on why this is also natural, due to *cognitive biases*, in his elaboration on the use of *heuristics* or 'rules of thumb' that approximate complex problem-solving situations, which *sustainable design practices* in turn include. Furthermore, other literature (see e.g., Mitnick (1992); Meyer and Rowan (1977); DiMaggio and Powell (1983)) support these claims. They argue that norms, or information with social origins, i.e., *cognitive biases*, are present and can dictate practices and change in organizations. Moreover, both Weber (2017) and Klotz et al. (2018), recently, add to this claim in the context of *sustainable design practices*.

The presence of *cognitive biases* becomes one key barrier to the adoption of *sustainable design practices* using design methods, but also to a *sustainability transformation* as such. Three hypothetical examples are provided to highlight how *cognitive biases* can lead to *pseudo-sustainable designs*.

- Designs or products that address the *design problem* of regional transportation (<1000 kilometers). For example, passenger cars that utilize electric drive trains, recyclable batteries, mega casting, and connected vehicles. In turn, reducing emissions in material acquisition, production,

[1] *Pseudo-sustainable designs* here refers to solutions that are intended to be sustainable but are not.

and use. However, the designs also systematically increase in weight, while at the same, the energy required to propel the cars also increases systematically with weight. Furthermore, the design also, at the same time, requires scarce resources that occasionally involve unequal labor, and in extreme cases child labor.

- Designs or products that address the *design problem* of global transportation (>1000 kilometers). For example, airplanes that utilize additive manufacturing, hybrid propulsion systems, alternative fuels, and low-weight designs with a vision of targeting net zero. In turn, reducing emissions in material acquisition, production, and in-flight. However, the designs are, at the same time, marketed and distributed to promote and reward extensive travel, via e.g., fly-more-cost-less campaigns leading to an absolute increase in emissions globally.

- Design or products that address the *design problem* of functional, protective, and comfortable clothing in varying weather conditions, along with occasional self-fulfillment needs (e.g., identity, expression, and symbolism). For example, the provision of clothes that utilize digital technologies in a closed-loop system. In turn, targeting resource-efficient material flows and reduced emissions. However, the design promotes a fast-paced change of clothes resulting in intense replacements of products and high material turnover making it difficult to achieve the intended benefits.

Argyris (1977; 2002a) notion of *single* versus *double loop learning* is not utilized in any of the papers but supports strengthening and highlights how *cognitive biases* can have a negative influence. That is, it can limit organizations from addressing the underlying problems as to why the adoption of *sustainable design practices* remains challenging, and design methods incorporating the *FSSD*.

5.1.5 The need for improved information and data capabilities

Papers B, C, and E all treat aspects related to the current information and data capabilities of the case companies, or the existing *digital infrastructure*, and it is also clear that it in many cases limits the appropriate adoption of design methods. It can either lead to inefficiencies when a lack of consideration results in additional steps that require time and resources to address e.g., incompatibility. Furthermore, there are also cases where design method outcomes are reduced when adaptations are made due to e.g., lack of valid information and data, which in turn leads to ineffectiveness in their use. This barrier becomes further evident when the design methods are embodied as computerized tools or software, which in turn need to be fitted or integrated into the current design process, or *method ecosystem*, and existing *digital infrastructure*.

This issue has been reported in previous studies (see e.g., Parolin et al., 2024; Booker, 2012), and currently limits the appropriate adoption of *sustainable design practices*, by e.g., reducing the scope of sustainability assessments.

Furthermore, Paper C highlights the internal issues of not having access to sufficient material data, which in turn limited the exploration of alternative solutions. However, Papers B and E also highlight this issue from a complete lifecycle, or value chain, perspective. This amplifies the issue as information and data need to be gathered from suppliers or other actors, causing obvious issues as data need to be shared with external actors. For example, treating intellectual property issues, a larger ecosystem of methods and software, and increased collaborative efforts consume additional time and resources.

All the cases have also shown that considering this *digital infrastructure* is tedious and in many instances also treating *contextual problems*. This in turn highlights issues related to the potential role a design researcher is expected to take in this aspect since the 'solutions' to these *contextual problems* will vary from organization to organization. Furthermore, proposing design methods based on currently available information and data aligns with a pragmatic approach to adoption. As Paper E highlights, such an approach can hinder the progression supporting the *paradigm of product design* to persist, which risks leading to *pseudo-sustainable designs*. However, embodying design methods in computerized tools and software has on the other hand been emphasized as important by several authors (Araujo et al., 1996; Thia et al., 2005; López-Mesa and Bylund, 2011; Gericke et al., 2020).

5.2 The role of design methods in the sustainability transformation

Papers B, C, D, and E highlight that the role of design methods can be expanded beyond what is mainly emphasized in the literature (see e.g., Eder, 1998; Wallace, 2011; Daalhuizen and Cash, 2021; Gericke et al., 2022). This additional role of new and improved design methods is relevant in contexts where appropriate adoption is challenging due to the extent of the process and methodological change required, such as in the *sustainability transformation*. It can be argued that the mindset in such a context is different since large-scale change is sought after, hence the term transformation. It is also necessary to move away from the *paradigm of product design* since it is insufficient to develop sustainable solutions.

5.2.1 Design methods as means for improving the information and data capabilities

Factor 51 - Design methods transfer understanding of 'how and what' sustainability relevant information and data to capture to practitioners is presented in Paper E. This factor indicates that design methods can support steering what information and data are required to adopt certain design practices. This can, in turn, support highlighting what information and data, ideally, need to be available to make appropriate assessments in *sustainable design practices*.

Paper B supports this finding as well, but instead on design practices focusing on how to design for additive manufacturing. Papers A, C, D, and E highlight this in the context of *sustainable design practices.* Furthermore, the use of such prescriptive design methods also supports aligning and streamlining terminology and understanding of concepts and terms used within these practices. This is in turn beneficial from a value chain perspective involving several actors with different views on what sustainability means. Furthermore, the use of such prescriptive design methods is also beneficial to meet traceability issues as their use lead to tracking and storing of results. Moreover, design methods have been claimed as effective means to improve accountability, record keeping, and traceability (Araujo et al., 1996; Eder, 1998; Eder, 2009), i.e., improving the information and data management capabilities of an organization.

5.2.2 Design methods as means for transferring design know-what

Factor 52 - design methods transfer 'design know-what' to practitioners is presented in Paper E. This factor indicates that design methods can as a means to both clarify and transfer knowledge about what ideal *sustainable design practices* are, i.e., what knowledge need to be produced, or what 'problems' need to be solved. This was conceptualized using the *situational design problem*, and that design methods can convey and/or transfer: 2) What *situational design problems* are relevant to the *design problem*; b) What knowledge about the *design problem* is relevant to produce. This can be further exemplified using established design methods such as Zwicky (1967) design method to generate concepts, and Pugh (1981) design method to screen concepts.

- The design method by Zwicky (1967) conveys to designers that it is 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 as it, for example, can lead to insights (i.e., knowledge) about what combinations of sub-solutions work, and what 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 effective to qualitatively compare different concepts, or solutions, systematically against previously identified criteria, or 'sub-problems'. This is effective as it, for example, can lead to insights (i.e., knowledge) about how to improve, and potentially merge, ideas or solutions to become even better solutions that can solve 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'.

5.2.3 Design methods as means for transferring design know-how

Factor 53 - design methods transfer 'design know-how' to practitioners is presented in Paper E. This factor indicates that design methods can act as a means to transfer knowledge about how to adopt *sustainable design practices*, i.e., how knowledge can be produced, or how 'problems' can be solved. This was conceptualized using the *situational design problem*, and that design methods can convey and/or transfer: 1) How to solve *situational design problems* relevant to the *design problem*; 3) How to produce knowledge relevant to the *design problem*. The design methods by Zwicky (1967) and Pugh (1981), exemplified above, 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, for 'less complex *design problems*', such *situational design problems* can be solved using pen and paper, and Excel-based tools. Furthermore, they can also be solved by integrating these facets into advanced computer tools to solve more complex *design problems*, such as the *Digital Design Experiments* used in Paper C. To summarize, the design methods highlight one of many ways to solve *situational design problems* of relevance. This proposal does, however, align with the current view of design methods as prescriptive 'know-how' (see e.g., Eder, 1998; Gericke et al., 2022) and provides limited new insights.

5.3 Facilitating the adoption of design methods

This research also provides answers to RQ3 that are presented and discussed in the coming sub-sections.

5.3.1 Actively considering aspects of change

Paper E and this thesis provide organizational and human-behavioral perspectives on a topic that has been challenging in design research for some time (see e.g., Eder, 1998; Gericke et al., 2020). These additional perspectives support explaining and clarifying why the adoption of design methods is a complex and multifaceted problem, and that adoption can be expected to be limited if not considered. Considering these aspects to a greater extent with caution will support increased chances of adoption, also illustrated in Figure 5.1. Furthermore, this research also highlights that design researchers, or *method experts* inside companies, need support and/or additional competencies in these aspects if the adoption of proposed design methods is desired (Boks, 2006; Pieroni et al., 2019). There are theories, frameworks, and models, such as Kotter (1995) or Deci et al. (2017), which can be utilized to facilitate the adoption of design methods. The findings of this research also highlight that practitioners, as receivers, of design methods need to be aware of these aspects to understand their role in the adoption of *sustainable design practices*.

5.3.2 Conceptual model of design methods as designs

The conceptual model (Figure 4.8) highlights that design methods can be considered as 'designs', which is supported and strengthened by previous literature. The model can be used to facilitate the adoption of design methods, since it acts as an effective means for bridging, i.e., simultaneously considering the three perspectives, i.e., process and methodological, organizational, and human-behavioral, which better clarify why adoption is challenging. For example, determine if the cause for low adoption is due to an irrelevant *situational design problem*, or if *contextual problems* are the cause for low adoption. Furthermore, it can for example also be used to understand if the lack of adoption is due to *cognitive biases* that in turn limit practitioners from having the intrinsic need to adopt the design method.

5.3.3 Needs driven and contextually adapted adoption

This research also made use of a new approach in the multiple case studies, which in turn aim to support design researchers, or *method experts*, to better understand the organizational context, or *method ecosystem*, in which the design method will be used. This approach required close collaboration with the industrial use case company as the research team identified answers to all steps together with the industrial team. The design researchers acted as facilitators and posed guiding questions to the industrial team, whereas they later verified the outcome of each step before entering the next. This approach consists of six distinct steps.

1. Use Case Formulation: The case company is initially asked to provide a high-level challenge or problem, and overall design context.

2. Scenario Breakdown: The high-level challenge is broken down into more specific needs or problems called scenarios where a case component is chosen to represent the scenario.

3. Generating an Idealised Design Process: Focus on understanding the design context of the case company, i.e., the typical design activities conducted by the company in the industrial use case scenario.

4. Design Method Need Identification: The industrial use case company is asked to identify the different *situational design problems* they have for each design activity in the design process.

5. Design Method Matching: This includes matching the *situational design problems*, or needs, with an a new and improved design method.

6. Execution: This is the actual application of the identified design methods and involves the industrial use case company.

This approach showed promising results in terms of understanding when, where, and how design methods fit, along with what type of adaptations are required. However, it requires further research as it has not been rigorously formalized, such as templates, and guiding questions. It also needs to be further rigorously evaluated and assessed. Furthermore, the approach is also intended to incorporate considerations related to the answers to the findings of this research, such as the conceptual model in 4.8, what aspects of the *digital infrastructure* need consideration, and how to foster autonomy via practitioner involvement to facilitate adoption.

5.3.4 Sustainable design thinking

Paper E proposes *Sustainable design thinking*, conceptually, as an effective means for addressing the *cognitive biases* present in organizations. This proposal is derived from **Factor 52 - design methods transfer 'design know-what' to practitioners**. The intention is that a supposed *Sustainable design thinking* systematically transfer relevant *design know-what*, and provide practitioners with a common understanding and base competence in *sustainable design practices*. Or what Eisenhardt (1999) refers to as a *collective intuition*, but acquired at all levels of the organization. This, in turn, requires two competencies:

- *Design competencies*, and refer to the principles of *designerly ways of knowing, thinking, and acting* which for example focus on the *co-evolution of problem-solution* and a better understanding of the *design problem* (see e.g., Cross, 1982; Dorst and Cross, 2001; Dorst, 2011; Cross, 2023a).

- *Sustainable design competencies*, and refer to the principles presented in the *Framework for Strategic Sustainable Development* (Broman & Robèrt, 2017).

Sustainable design thinking is not striving to disregard or substitute the role of e.g., sustainability experts, or designers with specialized knowledge in sustainable design in organizations. It is neither striving to substitute proven frameworks and design methods for sustainable design, such as the design methods used in the empirical study, or previously proposed design methods within eco-design, design for sustainability, and/or quantitative design methods (e.g., LCA). *Sustainable design thinking* mainly aims to develop base competence that can and needs to, be practiced by any *designer*[2], or *sustainable designer*[3], in organizations to systematically challenge the *cognitive biases* present in organizations. The *paradigm of sustainable design*, is here, argued to be entered when *Sustainable design thinking* is collectively understood, accepted, and practiced by a significant part of the practitioners inside an organization. Figure 5.3 (on the next page) illustrates how the amount of *Sustainable design thinkers* increases until it reaches a hypothetical 'critical mass' required to gain sufficient traction in the organization. This, in turn, enables the organization to accept and adopt *sustainable design practices* appropriately.

[2] "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (Simon, 1969)

[3] "If you try to ensure long-term human well-being within the limits of the natural world, then you design for sustainability" (Klotz et al., 2018)

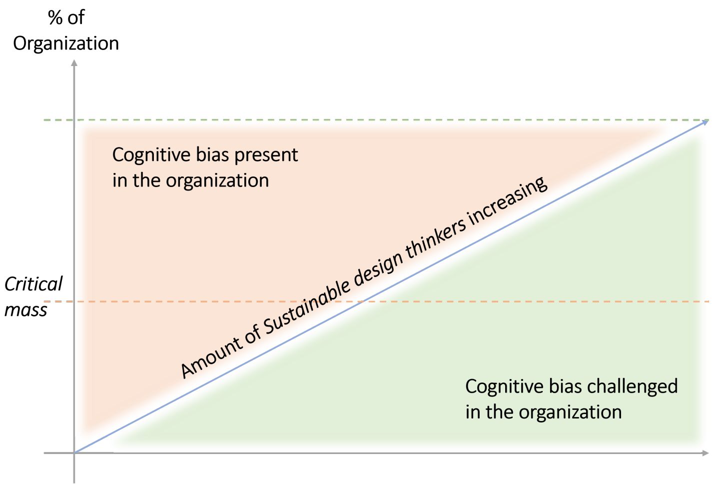

Figure 5.3: Figurative example of how the *cognitive biases* in an organization needs to be challenged until it reaches a hypothetical 'critical mass' that enables the organization to appropriately adopt *sustainable design practices*.

There are also additional considerations related to e.g., supplier involvement in the design process, which can be facilitated by such an approach. Organizations need to look beyond their operations and consider the sustainability performance of the complete value chain to align with the FSSD. *Sustainable design thinking* should also strive to embody what the *paradigm of design thinking* (Brown et al., 2008; Brown and Katz, 2011; Verganti et al., 2021) has done to successfully gain traction in different problem-solving practices.

This proposition is based on the findings of this thesis but require further research. *Sustainable design thinking* has not been rigorously formalized, and it also needs to be tested, evaluated, and assessed, with the disclaimer that such a proposition will be unrealistic to validate as it is broad in its claim. However, the overall claim that a *Sustainable design thinking* approach can challenge *cognitive biases* is supported by e.g., Liedtka (2015) and also the notions of *Double loop learning* as framed in Section 3.9. Furthermore, *Sustainable design thinking* will not be developed from scratch, but focus on identifying and integrating a set of existing design methods that target the 'most relevant' *situational design problems*.

5.4 Validity of the findings

It is appropriate to discuss the validity of the findings for each RQ as this research mainly has focused on ensuring that the answers to RQ1 are valid and reliable. The answers to RQ2 are a 'byproduct' from the analysis that answers RQ1 and share equal reliability and validity.

Several strategies were used to ensure validity in the findings aimed to answer RQ1 as described in Section 2.7. The analysis that provided the base for answering RQ1, i.e., the descriptive framework, made use of a rigorous inductive analysis using *Glaserian Grounded Theory.* This analysis made use of a large sample of qualitative empirical data using multiple cases, complemented with theoretical sampling from data captured in seminars from Project A. Furthermore, insights and findings from Project B and efforts within EWB-SWE are also brought in to strengthen the answers to RQ1. This in turn supports to generalize of the results further and strengthens their *external validity* (Säfsten & Gustavsson, 2020). The results were also compared to previous studies to further strengthen its validity, and streamline terminology.

The researcher's bias and role have also been presented in what can be considered transparent to further clarify how that potentially could have influenced the results of this research. Peer debriefing has also been done in different ways, such as testing ideas with peers, but also involving peers in rigorously checking the coding process that was carried out in Paper E.

One limitation, or weakness, of the adopted research approach and the findings of this research, concerns its 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 data and analysis. The raw data and analysis are accessible, which makes it possible to scrutinize the procedure externally and also revisit the source data. Furthermore, the correspondence criteria also aimed to support that appropriate codes were assigned. It is, however, difficult to justify that the same codes would be assigned if another researcher conducted the analysis. The codes generated during the *Glaserian Grounded Theory* analysis have, on the other hand, been 'approved' by the co-authors. The co-authors more specifically compared the raw data to the assigned code to ensure there was appropriate correspondence.

The answers to RQ3 are rather seen as unverified and unvalidated propositions and their validity is therefore not appropriate to discuss in detail in this thesis. This will instead be part of the future work that focuses on the Prescriptive study and Descriptive study II, i.e. after they have been appropriately formalized and assessed. However, one strength of these key propositions is that they build on previous research, and the propositions mainly focus on clarifying how these 'pieces' potentially fit together, by considering both the process and methodological, organizational, and human-behavioral perspectives simultaneously.

Chapter 6

Conclusions and future research

This chapter will present the conclusions of this research, how it contributes to new knowledge, and what future work is required.

6.1 Conclusions

This research aimed to increase the understanding of what currently limits adoption, how to facilitate adoption, and how design methods can increase the ability to design more sustainable solutions. The scope of this research was also to explore this and provide new insights by considering the three perspectives, process and methodological, organizational, and human-behavioral.

The first part of this aim is fulfilled by providing answers to RQ1: *What barriers influence the adoption of sustainable design practices using new and improved design methods?* Given the results from this research, five key barriers are concluded to provide answers to RQ1:

- *The prescriptive nature of design methods and the influence of human-behavioral aspects*: This research has shown that adopting design methods is set to fail if such aspects are neglected, or not appropriately considered.
- *The contextual complexity of design method adoption*: This research has shown that there is always a need to adapt design methods to the targeted context. This is, in turn, a non-straightforward and resource-consuming activity, and it is not clear what actor, i.e., the practitioner, *method expert*, or design researcher, should be responsible for such adaptation.
- *The need for a paradigm shift in how design is practiced in the manufacturing industry*: This research has shown that the current design practices in the manufacturing industry lack the appropriate incorporation of a systemic perspective to sustainability, and are insufficient to design sustainable solutions and require radical changes.

- *The presence of cognitive biases that lead to a state of pseudo-sustainability*: This research has shown that there are *cognitive biases* present in organizations that limit the ability to appropriately adopt *sustainable design practices*. This, in turn, results in a risk of proposing non-sustainable solutions.

- *The need for improved information and data capabilities*: This research has shown that the current information and data capabilities are insufficient to effectively and efficiently adopt *sustainable design practices*, and new and improved design methods as such.

This research showed that role to be **design methods as means for** (i) improving the information and data capabilities of an organization. (ii) Transferring *design know-what*, and (iii) *design know-how* to practitioners. This answers RQ2, fulfilling parts of the aim of this research, and expands the role a design method can have in increasing organizations' ability to design more sustainable solutions.

The results of this research also provide answers to RQ3 fulfilling the remaining aim of this research. This research has shown that appropriate *consideration of organizational and human-behavioral perspectives* can facilitate and increase the chances of practitioners adopting design methods. It is also highlighted that design researchers, or *method experts* inside companies, need support and/or additional competencies to consider these aspects. This is further supported by previous literature.

6.2 Scientific contributions

This thesis has also supported generating new knowledge to design science that is relevant to design researchers and practitioners.

- The five key barriers identified have been reported on previously but scattered across different research domains. The novel contribution to the knowledge in this research is how these key barriers are framed from both process and methodological, organizational, and human-behavioral perspectives.

- To the best of the author's awareness regarding the answers to RQ2, (ii) is a novel contribution to knowledge, whereas (i) and (iii) are highlighted by previous literature.

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

6.3 Future work

The results from this research pave the way for future research with an added focus on the prescriptive parts of the formulated research aim, i.e., answering RQ3 with greater detail. This research provides two key propositions.

- The adoption of design methods can be facilitated if it is needs-driven and the design method is adapted to contextual circumstances. A *Needs-driven and contextually adapted adoption* approach was proposed to address this, but it requires further work going forward. This will focus on formalizing the approach and assessing its use in supporting needs-driven and contextually adapted adoption.

- The adoption of *sustainable design practices* using design methods can be facilitated if *cognitive biases* are systematically challenged in organizations. A *Sustainable design thinking* approach was proposed to address this, but it requires further work and development going forward. This will focus on aspects such as what characterizes such an approach, what design methods should embody the approach, and how can it be formalized and communicated effectively. Its use in systematically challenging *cognitive biases* will also be assessed.

This can further result in the RQs, and especially RQ3, being reformulated or changed to better align with the results from the future work that is expected to be carried out.

References

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

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

Aken, J. E. v. (2004). Management research based on the paradigm of the design sciences: The quest for field-tested and grounded technological rules. *Journal of management studies*, *41*(2), 219–246.

Appelbaum, S. H., Habashy, S., Malo, J.-L., & Shafiq, H. (2012). Back to the future: Revisiting kotter's 1996 change model. *Journal of Management development*, *31*(8), 764–782.

Araujo, C. (2001). *Acquisition of product development tools in industry: A theoretical contribution* [Doctoral dissertation, Technical University of Denmark].

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 Engeering Design*, *7*(3), 265–277.

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

Argyris, C. (1977). Double loop learning in organizations. *Harvard business review*, *55*(5), 115–125.

Argyris, C. (1996). Actionable knowledge: Design causality in the service of consequential theory. *The Journal of applied behavioral science*, *32*(4), 390–406.

Argyris, C. (2002a). Double-loop learning, teaching, and research. *Academy of management learning & education*, *1*(2), 206–218.

Argyris, C. (2002b). Teaching smart people how to learn. *Reflections-society for organizational learining*, *4*(2), 4–15.

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.

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

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.

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

Brown, T., et al. (2008). Design thinking. *Harvard business review*, *86*(6), 84.

Brown, T., & Katz, B. (2011). Change by design. *Journal of product innovation management*, *28*(3), 381–383.

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.

Bunge, M. (1966). Technology as applied science. In *Contributions to a philosophy of technology: Studies in the structure of thinking in the technological sciences* (pp. 19–39). Springer.

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

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.

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.

Daalhuizen, J., & Cash, P. (2021). Method content theory: Towards a new understanding of methods in design. *Design Studies*, *75*, 101018.

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/

Design Council. (2021). Beyond net zero: A systemic design approach. *London: Design Council. Retrieved February*, *7*, 2022.

DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American sociological review*, *48*(2), 147–160.

Dorst, K. (2006). Design problems and design paradoxes. *Design issues*, *22*(3), 4–17.

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.

Eckert, C., McMahon, C., & Stacey, M. (2023). What counts as design? no one right answer. In *Expanding the frontiers of design: Critical perspectives* (pp. 38–55). Taylor & Francis.

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). Agency theory: An assessment and review. *Academy of management review*, *14*(1), 57–74.

Eisenhardt, K. M. (1999). Strategy as strategic decision making. *MIT Sloan Management Review*, *40*(3), 65.

Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: What are they? *Strategic management journal*, *21*(10-11), 1105–1121.

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

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).

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.

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*.

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

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. *Handbook of qualitative research*, *2*(163-194), 105.

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.

Hallstedt, S. I. (2017). Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of cleaner production*, *140*, 251–266.

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., Thompson, A. W., & Lindahl, P. (2013). Key elements for implementing a strategic sustainability perspective in the product innovation process. *Journal of cleaner production*, *51*, 277–288.

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.

Herstatt, C., & Verworn, B. (2004). The 'fuzzy front end' of innovation. In *Bringing technology and innovation into the boardroom: Strategy, innovation and competences for business value* (pp. 347–372). Palgrave Macmillan UK. https://doi.org/10.1057/9780230512771_16

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.

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.*

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.

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.

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.

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

Kotter, J. P. (2012). *Leading change.* Harvard business press. https://kingdomwayministries.net/wp-content/uploads/2016/12/Leading_Change_2col.pdf

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.

Liedtka, J. (2015). Perspective: Linking design thinking with innovation outcomes through cognitive bias reduction. *Journal of product innovation management*, *32*(6), 925–938.

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.

Lönngren, J., & Van Poeck, K. (2021). Wicked problems: A mapping review of the literature. *International Journal of Sustainable Development & World Ecology*, *28*(6), 481–502.

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.

Magistretti, S., Ardito, L., & Messeni Petruzzelli, A. (2021). Framing the microfoundations of design thinking as a dynamic capability for innovation: Reconciling theory and practice. *Journal of Product Innovation Management*, *38*(6), 645–667.

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. (2022). Assessment of weld manufacturability of alternative jet engine structural components through digital experiments. *ISABE*, *2022*.

Meyer, J. W., & Rowan, B. (1977). Institutionalized organizations: Formal structure as myth and ceremony. *American journal of sociology*, *83*(2), 340–363.

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

Mitnick, B. M. (1973). Fiduciary rationality and public policy: The theory of agency and some consequences. *1973 Annual Meeting of the American Political Science Association, New Orleans, LA. In Proceedings of the American Political Science Association.*

Mitnick, B. M. (1992). The theory of agency and organizational analysis. *Ethics and Agency Theory: An Introduction (New York: Oxford University Press, 1992)*, 75–96.

Mitnick, B. M. (2019). Origin of the theory of agency: An account by one of the theory's originators. *Social Science Research Network Electronic Journal*.

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.

Niiniluoto, I. (1993). The aim and structure of applied research. *Erkenntnis*, *38*(1), 1–21.

O'Connor, G. C. (2008). Major innovation as a dynamic capability: A systems approach. *Journal of product innovation management*, *25*(4), 313–330.

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

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

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).

Produktion2030. (2024). Impact Innovation programmet-Net Zero Industry har godkänts! Retrieved April 8, 2024, from https://produktion2030.se/impact-innovations-programmet-net-zero-industry-godkants/

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

Quella, F., & Schmidt, W.-P. (2003). Integrating environmental aspects into product design and development the new iso tr 14062. *The International Journal of Life Cycle Assessment*, *8*, 113–114.

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.

Reid, S. E., & De Brentani, U. (2004). The fuzzy front end of new product development for discontinuous innovations: A theoretical model. *Journal of product innovation management*, *21*(3), 170–184.

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

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, S. A. (1973). The economic theory of agency: The principal's problem. *The American economic review*, *63*(2), 134–139.

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

Sahakian, J., & BenMahmoud Jouini, S. (2023). Building design as a dynamic capability: A model for design integration. *Journal of Product Innovation Management*, *40*(5), 733–758.

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.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. *Knowledge-based systems*, *5*(1), 3–14.
Shapiro, S. P. (2005). Agency theory. *Annual Review of Sociology*, *31*, 263–284.
Simon, H. A. (1969). The sciences of the artificial. *The MIT Press*.
Simon, H. A. (1979). Rational decision making in business organizations. *The American economic review*, *69*(4), 493–513.
Sumter, D., De Koning, J., Bakker, C., & Balkenende, R. (2020). Circular economy competencies for design. *Sustainability*, *12*(4), 1561.
Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic management journal*, *18*(7), 509–533.
Thia, C., Chai, K.-H., Bauly, J., & Xin, Y. (2005). An exploratory study of the use of quality tools and techniques in product development. *The TQM Magazine*, *17*(5), 406–424.
Thomas, J. C., & Carroll, J. M. (1979). The psychological study of design. *Design studies*, *1*(1), 5–11.
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.
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/
Verganti, R., Dell’Era, C., & Swan, K. S. (2021). Design thinking: Critical analysis and future evolution.
Vilochani, S., McAloone, T. C., & Pigosso, D. C. (2024). Consolidation of management practices for sustainable product development: A systematic literature review. *Sustainable Production and Consumption*.
VINNOVA. (2024). Cirkularitet - FFI - våren 2024. Retrieved April 8, 2024, from https://www.vinnova.se/e/utlysning-2022-00048/cirkularitet-ffi-varen-2024/
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., & 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.

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.

World Business Council for Sustainable Development. (2021). Time to Transform. Retrieved April 8, 2024, from https://www.wbcsd.org/Overview/About-us/Vision-2050-Time-to-Transform/Resources/Time-to-Transform

World Economic Forum. (2022). What the IPCC Report tells us about the need for radical climate action. Retrieved April 8, 2024, from https://www.weforum.org/agenda/2022/03/what-the-ipcc-report-tells-us-about-the-need-for-radical-climate-action/

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/

Zollo, M., & Winter, S. G. (2002). Deliberate learning and the evolution of dynamic capabilities. *Organization science*, *13*(3), 339–351.

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.