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On Material Selection and its Consequences in Product Development

Fredrik Henriksson

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Längst, djupast i ändlösa skogar, bakom urberg, stupande grå,
bortom svindlande, ändlösa hedar, där dagarna dödstysta gå,
där jäser i smältvit hetta ett bål under stybbade bryn
och silar ur hundra små gluggar sin gråa rök mot skyn.

Där kring går en nattsvart mänska med ögon som vitt porslin
och svettas i kamp mot hungern och med bröstet mot vinterns lavin.

All eld som brinner är eld, fast den göms som vore den död,
all eld är äkta eld, fast den ej lyser som druvor röd.

Den glöder ändå där nere, den bränner sig längre ner,
och gräver sig ut och flammar i natten, när ingen ser.

Så glöder, så brinner en mänska av hat, av hopp och tro,
så går från djupet små rökmoln och somna i skogarnas ro.

Så stiga den gömdes visor ur jord och bränder fram,
och smyg sig drömmande ut över urbergens trasiga kam.

Det hela är röken bara av en ande som trotsar och ber
det är grått, det är släckt, det försvinner, det är milrök - ingenting mer.

Dan Andersson (Milrök I)

Abstract

Technological development, and increased demands for sustainable solutions, have impacted the development of new products. New products need to be more efficient, and there are increased possibilities for a more diversified and informed decision regarding what materials are used in the product. However, how can engineers and designers be helped in their efforts to make better decisions regarding materials?

In this research, carried out via multiple case studies and action research, behaviors regarding material selection and material management are examined. The data has been collected using participation action research, observations, and interviews as the primary sources of information. The author has conducted participation action research integrated into an industrial environment, multiple case studies using students in industrial design engineering have been done, and the researcher has performed interview studies with industry representatives. The behaviors described in the empirical studies are contrasted with basic decision theory and analysis of established product development methodology, in an attempt to partly answer a much larger question: Are some of the basic assumptions built into models and methods taught to designers and engineers valid?

The research presented in this thesis shows that there are personal, technical, and organizational aspects to selecting and managing materials in product development. This work has also shown that assuming rationality, something that is built into methods and models as well as taught to engineering students, is not valid in decision-making; human beings are not rational, and entirely rational decisions are not possible due to the vast data and prediction capabilities needed to be able to make entirely rational decisions. Even when assuming some variant of bounded rationality, multiple factors described in decision theory are not fully acknowledged in product development methodology. Two of these can be described as identity (both personal and professional) and mental models of materials.

The discrepancy in how decisions are described in decision theory and how methods for decision-making are designed in product development risks inhibit the introduction of new and more sustainable materials in products. This could be because non-rational aspects of decision-making are incorporated in the decision-making under the assumption of rationality. It could also be because of the mental models of materials affecting what the designers and engineers think they can do with a particular material. These behaviors could make the risks of introducing new materials too big for a designer or engineer to accept.

In this thesis, the author shows that additional data will not be enough to persuade designers and engineers to select new material to its fullest extent. This can slow down sustainability improvements in products. To counter this, it is suggested that the personal and non-rational side of decision-making is acknowledged and valued, that visions and ideology are used to encourage the introduction of new materials (rather than relying on only technical or economic aspects), and that designers and engineers should be encouraged and enabled to take higher risks and evaluate more “unknown” parameters without feeling that they risk derailing a project.

To fully implement these suggestions, the following three things need to happen:

- Design and engineering education needs to teach students how to have more flexible mental models of materials
- Industry should find ways for designers and engineers to experiment further and learn (both on an organizational and personal level)
- Academia should further investigate how behaviors, mental models and habits affect product development and design work, especially regarding material selection and material management

Populärvetenskaplig sammanfattning

Den tekniska utvecklingen, kombinerat med högre ställda krav på hållbara lösningar, har påverkat utvecklingen av nya produkter. Nya produkter måste vara effektivare än tidigare, och det finns en större möjlighet att ta mer diversifierade och bättre informerade beslut med avseende på vilka material som ska användas i en produkt. Men hur kan ingenjörer och designers hjälpas att ta mer hållbara och bättre beslut kring material? I ett antal fallstudier, som använt sig av aktionsforskning, observationer och intervjuer som främsta datainsamlingsmetoder, har beteenden kring materialval och materialhantering i produktutveckling undersökts. Dessa beteenden och metoder har sedan kontrasterats mot grundläggande beslutsteori, för att förstå huruvida grundläggande antaganden som byggts in i modellerna och verktygen är rimliga.

Forskningen som presenteras i denna avhandling visar på att det finns personliga, organisatoriska och tekniska aspekter som påverkar materialval och -hantering i produktutveckling. Arbetet har också visat att det antagande om rationalitet, som metoder och verktyg baserats på och som lärs ut till ingenjörsstudenter, inte är ett valid antagande i beslutfattande; människor är inte rationella och perfekt rationella beslut är inte möjliga baserat på den mängd data och den kunskap om framtida utfall som krävs för att ta rationella beslut. Inte ens begränsad rationalitet (bounded rationality) kan användas för att beskriva produktutvecklingens syn på beslut, då produktutvecklingsteori saknar begrepp som identitet (professionell och personlig) och mentala modeller av material i sin förklaring av beslutsfattande.

Skillnaderna mellan hur beslutsfattande beskrivs i beslutsteori, och hur de hanteras i produktutvecklingsmetodik, riskerar att begränsa hur nya och mer hållbara material kan användas i nya produkter. Detta då de icke-rationella faktorer som inte belyses som varandes just icke-rationella i diskussioner om produktutvecklingsmetodik, riskerar att påverka vad ingenjörer och designers tror sig kunna göra med ett visst material. Detta riskerar att risker upplevs för stora, och att material därför underutnyttjas.

Utfall från den här forskningen visar att mer information inte kommer att vara tillräckligt för att övertyga ingenjörer och designers om att använda nya material till sin fulla potential. Det här riskerar att försena hållbara omställningar i produkter. För att motverka detta, föreslås i denna avhandling att icke-rationella aspekter i beslutsfattande belyses, accepteras och uppvärderas, att visioner målbilder används för att introducera nya material snarare än tekniska eller ekonomiska aspekter, och att ingenjörer och designers får möjlighet och uppmuntras att ta större risker och hantera fler okända parametrar längre in i produktutvecklingsprojekt.

För att implementera dessa förslag, behöver följande saker ske:

- Utbildningen av ingenjörer och designers behöver ändras för att hjälpa studenterna att experimentera och ha mer flexibla mentala modeller av material
- Industrin behöver möjliggöra experiment och lärande kring nya material (både på organisatorisk och personlig nivå, för alla som arbetar med produktutveckling)
- Akademien behöver arbeta för att förstå hur beteenden, mentala modeller och vanor påverkar produktutveckling, speciellt med avseende på materialval och hantering av material

Appended studies & author contributions

1: On material substitutions in automotive BIWs

Henriksson was the main contributor to the paper, responsible for data gathering and analysis and the paper's writing. Johansen gave support and feedback on the manuscript before submission. *Presented at CIRP 2016, published in Procedia CIRP. Full text in Appendix 1.*

Complete reference: Henriksson, F.; Johansen, K. (2016): "On Material Substitution in Automotive BIWs – From Steel to Aluminum Body Sides." 26TH CIRP DESIGN CONFERENCE / [ed] Wang, Lihui; Kjellberg, Torsten, Elsevier, 2016, Vol. 50, pp. 683-688. DOI: 10.1016/j.procir.2016.05.028

2: Assumptions of wood

Henriksson was the main contributor to the paper, responsible for data gathering and analysis and the paper's writing. Johansen and Schütte aided in the development of the paper, Johansen worked as a co-supervisor in some of the projects where data was gathered, and both Johansen and Schütte gave support and feedback on the manuscript before submission. *Submitted to FORMAkademisk November 2020. Full text in Appendix 2.*

Complete reference: Henriksson, F.; Schütte, S.; Johansen, K. (2020): "Assumptions of wood as a design material: Case studies on industrial design engineering students in Sweden." Submitted to FORMAkademisk in November 2020.

3: Multi material solutions in the automotive industry

Henriksson was the main contributor to the paper, responsible for data gathering and analysis and the paper's writing. Johansen contributed with parts of the text regarding production and flexibility and gave support and feedback on the manuscript before submission. *Presented at SAE World Congress 2016, published in SAE Technical Paper Series. Full text in Appendix 3.*

Complete reference: Henriksson, F.; Johansen, K. (2016): "An outlook on multi material body solutions in the automotive industry – possibilities and manufacturing challenges." SAE Technical Paper Series, SAE 2016 World Congress and Exhibition. DOI: 10.4271/2016-01-1332

4: Knocking on wood

Henriksson was the main contributor to the paper, designed the interview study and conducted the interviews, analyzed the data, and wrote the majority of the paper. Johansen and Schütte aided in the development of the study, Schütte acted as the internal respondent in a test interview, and both Johansen and Schütte gave support and feedback on the manuscript before submission. *Accepted for publication by International Journal of Sustainable Engineering August 2021. Full text in Appendix 4.*

Complete reference: Henriksson, F.; Johansen, K.; Schütte, S., (2020): “*Challenges when working with renewable materials: Knocking on wood?*” Revision accepted International Journal of Sustainable Engineering in August 2021, currently in editorial copy-editing process.

5: Production – as seen from product development

Henriksson and Detterfelt acted as equal co-authors, collaborating on the design of the study and the data gathering and analysis. The paper was also written as a collaboration. *Presented at NordDesign 2018. Full text in Appendix 5.*

Complete reference: Henriksson, F.; Detterfelt, J., (2018): “*Production – as seen in product development: A theoretical review of how established product development process models address the production system*” DS 91: Proceedings of NordDesign 2018: Design in the Era of Digitalization. ISBN: 978-91-7685-185-2

6: Introducing new materials in the automotive industry

Henriksson is the sole author of this work, with supervisory help from Johansen, Detterfelt, and Ölvander in giving support and feedback on the manuscript before submission. *Thesis excerpt presented and published October 2017. Full text in Appendix 6.*

Complete reference: Henriksson, F. (2017): “*Introducing New Materials in the Automotive Industry: Managing the Complexity of Introducing New Materials in Existing Production Systems.*” Linköping: Linköping University Electronic Press, Linköping Studies in Science and Technology, pp. 87-99, 2017. DOI: 10.3384/lic.diva-142873

7: Framework for introducing new materials

Henriksson, Detterfelt and Davidsson designed the study together. Henriksson then acted as the participating researcher, gathering data continuously. Johansen and Detterfelt aided with documenting the debriefing sessions, and Henriksson did the primary analysis. Henriksson wrote the main bulk of the paper, with Detterfelt and Davidsson giving support, feedback, and suggestions on the manuscript before submission. *Published in SAE Journal of Materials and Manufacturing November 2020. Full text in Appendix 7.*

Complete reference: Henriksson, F.; Davidsson, A.; Detterfelt, J., (2021): “*Introduction of New Materials in the Automotive Industry: A Case Study-Based Framework.*” SAE International Journal of Materials and Manufacturing, 14(1):99-110, 2021. DOI: 10.4271/05-14-01-0008

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Okay, so I'm actually almost done? It does sound unlikely, but I just have to believe, I guess. This has been a journey, a journey with both ups and downs. But most of all, it has been a journey where a lot of people have stretched out a hand to help. Mentioning everyone by name is impossible, but why not try anyway?

First, I want to thank all of my supervisors, who have help me get here. Thank you, Kerstin, for all discussions on road trips between Linköping and Göteborg. You have broadened my understanding of research, and what it can become.

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I also want to thank my friends and family, for supporting, listening, and in general just tolerating my rants, reflections, and stubbornness to the degree that you have. Thank you for being there, for making me carry on when I doubted it and for dragging me away when I needed a break. Thank you for all the time and all the discussions. Your understanding and support have made this possible, and made me a better person along the way. And if I continue to hark on about this in the future, please hit me on the head with a rather firm stick.

Farfar och mormor: Jag är ledsen att ni aldrig fick möjlighet att se vad det blev av mig när jag till slut hade studerat klart, eller läsa den här boken. Men jag lovar; det ska nog bli något vettigt av mig också, till slut.

And now for something completely different.

Linköping, August 2021

Contents

1	Introduction	1
1.1	Background	1
1.2	Aim and objectives	4
1.3	Research questions	4
1.4	Assumptions	4
1.5	Limitations and delimitations	5
1.6	Definitions	6
2	Methodology	11
2.1	General research process	12
2.2	Literature reviews	13
2.3	Case studies	16
2.4	Interview studies	18
2.5	Action research	21
2.6	General methodological reflections	23
3	Theoretical framework	29
3.1	Product development and design	29
3.2	Production system development	36
3.3	Decision theory and analysis	42
4	Findings and analysis	51
4.1	Contribution from studies	51
4.2	Summarizing the studies	52
4.3	Analysis	54
4.4	Discussion	63
5	Exemplifying material decisions	71
5.1	Design fiction	71
5.2	The company and project team	73
5.3	The decision-making process	76
6	Conclusions	85
6.1	Contributions	89
6.2	Future work – what is to come?	91

1 Introduction

“We are stuck with technology when what we really want is just stuff that works.”

Douglas Adams, *The Salmon of Doubt* (2002)

In a constantly changing world, we also need to reexamine the products we aspire to bring into this world. We need to make products that are more sustainable, more reliable, easier to use, and not a downgrade than the ones of yesterday in any way, shape, or form. The people that develop products need to solve all this while still being more efficient and working in shorter development cycles. These aforementioned factors mean that we also need to reexamine and reinvent how we make products: both in development and production.

It is unlikely that today’s product development methods will solve tomorrow’s problems, at least if we generalize Albert Einstein’s famous words on problem-solving (“*a new type of thinking is essential if mankind is to survive and move to higher levels*” from Einstein & Amrine, 1946). Nevertheless, how can we improve the methods to make the right thing more effortless for those who need to do the right thing? Understanding the path that the development of methods for product realization should be following can aid in bringing in these new methods sooner and more efficiently. How can we make the most out of the new technology being developed and get it to become the stuff that just works, the stuff that helps people solve their problems? Furthermore, what will tomorrow’s designers and engineers need to have fulfilling work and sustainably create the best possible products?

1.1 Background

According to the UN global goals for sustainable development, society needs to create new sustainable production and consumption patterns (United Nations, 2020) and encourage more sustainable innovation and industrialization (United Nations, 2020) to create a viable future for all humankind. This change, of course, involves changes in both products and production. In order to fulfill this, sustainability must be fully integrated into the product realization process since modification costs are low (Lindahl, 2005) and possible sustainability improvements are high (Chebaeva, et al., 2021) early on in a product development process. At another end of the product realization process, production is another major contributing factor to resource management and product revenue (Bellgran & Säfsen, 2010). In this

intersection between product development, production and sustainability, there should be tools and processes. Tools and processes that are defined to actually help a designer or engineer solve problems when developing new products to ensure that the development can be done in a sustainable way for all actors.

In an effort to create more sustainable products, the industry has started to evaluate the materials used in products: Can they be switched to more sustainable ones? Maybe even renewable materials? The answer is not clear-cut and universal for all products, and there might not even be a gold standard to adhere to. However, increased usage of sustainable and renewable materials is not only possible but a necessity. So how can these materials be utilized?

Material selection methodology, a topic that is relevant to the questions asked in the previous paragraph, is a well-defined topic in design and engineering literature, with both general (Ashby, 2005) and more specialized methods (Karana, et al., 2010; Hallstedt & Isaksson, 2017) being presented in the literature. However, these are often prescriptive methods, explaining how something *should* be done. Are these methods used, and are they suited to be implemented in industry or education? Descriptive studies are done, for example by Karana, et al. (2007), but more seldom. A deeper understanding of how designers and engineers select material might give insights on how applicable existing prescriptive methods are and how new methods should be designed.

Multiple studies on material substitution have been done and published, but they often have one of two viewpoints; looking at a specific industry or type of product where Poulikidou, et al. (2015) can be used as an example, or looking at how a specific material can be introduced, where Jonsson (2006) and Boehner, et al. (2017) can be highlighted as examples. Sometimes, both these perspectives are applied simultaneously, especially in case studies (Smith & Kienhöfer, 2015). All of this is, of course, relevant research and very interesting for both academia and industry, and brings engineering and design theory building forward. However, much of the generated knowledge cannot be reused for “the next material” or a new product. Instead, the designers and engineers are left to rediscover the same challenges when the next material comes around. What can be done to help designers and engineers on a more general level? If there is a possibility to give suggestions on how to introduce *any* new material in *any* product category, this type of generalized knowledge can make future technology and material shifts more efficient and effective.

There are also studies on how new materials can be a driver for developing new products (Karana, et al., 2015), but these methodologies are more intuitively aimed at materials that are in development or not yet fully industrialized. Since these methods bring new viewpoints to the body of knowledge, can these viewpoints also be used in more traditional projects? If these methods can be applied to work better with established materials and be included in established product development processes, they can contribute with the added understanding of how material selection affects product realization. Also, it is valuable to evaluate if the methods can help developers understand a new material to the extent needed to be able to use it in a project.

This thesis centers around product development. Product development can be defined as “*the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale*” (Krishnan & Ulrich, 2001). Product development processes, the recipe for product development or the description of how tasks are sequenced in the workflow (Henriksson, 2017), have been abstracted and described for well over 50 years with early industrial contributions in the field dating back to the mid- or post-war era in the first half of the 20th century (McGrath, 2004). Many different takes on the process to develop a product has been made over the years (Andreasen & Hein, 1986; Cooper, 1990; Ulrich & Eppinger, 2008; Johannesson, et al., 2013), but the main inputs and outputs are usually the same: you start with a customer problem or need, and end up with a definition of a product similar to the definition from Krishnan & Ulrich (2001). These methods need rework to be applied in projects and tend to assume a linear progression through a project. Since this thesis is about non-automated development, i.e., including human decision-makers, it is also valuable to understand how the actors in a project can affect the product realization process.

During the writing of this thesis, the COVID-19 pandemic of 2020 and 2021 (and hopefully not much longer), has brought the topic of flexibility (especially production flexibility) into the public spotlight again. Multiple companies have been transitioning from their main products to different types of hospital equipment (SVT, 2020; CNN Business, 2020; Fast Company, 2020), showing the possibility and challenges of retuning your production system to a new product. The task is big: changing a production line to make something it has never done before, with high demands on quality and production volumes, is not as easy as it first seems. Others have had to readjust their business model to stay relevant (The Manufacturer, 2020). These tasks come on top of significant, systemic changes in, for example, electrification of the automotive industry (Fyhr, 2018) and worldwide shifts toward eliminating single-use plastics (Masterson, 2020), two trends that have had, and will continue to have, distinct effects on the design of different products. The topic of flexibility in production in itself is well researched (Browne, et al., 1984; Sethi & Sethi, 1990; Gerwin, 1993) and has an intimate connection to product development, especially for companies with multiple products being produced at the same site. Flexibility in this sense is also relevant for introducing new materials in products; we might have to use multiple materials in the new design, and these might have vastly different properties. The production system might manage these variations with its built-in flexibility, or the material selection possibilities will be limited by the possibilities within the production system boundaries. Being able to predict this could help the industry making better informed strategic decisions.

When looking at how new products can be made more sustainable, all of this should be included; material selection and management of material-related issues after the initial selection is made, new methods of managing material-related challenges in product realization, product development processes, and production challenges. But how is it done today, and what can be done better? This thesis explores this in one aspect of the product development process; the selection and use of material when developing new products.

1.2 Aim and objectives

The aim of this research is to explore how the decision-making process in product realization is done and if the tools and methods used today are suitable for helping developers make decisions. This will be done in the context of material selection and managing of subsequent material-related challenges in product realization.

The objectives are to:

- Identify and describe developers' understanding of materials and production processes
- Describe some relevant (for product realization) behaviors and logics for decision making in project teams and how these behaviors and logics affect material selection in product realization
- Make recommendations for product development work and related education, that could improve quality in the material selection process

Please see 1.6.1 for a definition of a developer. As a long-term effect goal of this research, product realization could be made more efficient by creating better, more sustainable, products and reducing the risk for project failure. Project failure, in this case, can be both projects abandoned in later stages of the development process, faulty products launched to market, and projects getting significant criticism in an evaluation according to the product development project characteristics described by Ulrich and Eppinger (2008).

1.3 Research questions

In order to fulfill the aim and objectives presented earlier, three research questions have been formulated. In this thesis, I aim to answer the following research questions:

RQ 1: How are developers interacting, mentally and physically, with the materials and the production process when developing a new product?

RQ 2: What parts of decision theory and analysis could be relevant for product development in general, and material selection in specific, in order to develop new methods and tools for developers?

RQ 3: What can be done within this interaction between developer and material, to reduce the risk for failure when selecting materials and when using new materials in products?

1.4 Assumptions

In order to create a context and some boundaries for this thesis, some limitations and assumptions will be made. The significant assumptions are described here.

An underlying assumption for this work is that product development processes and tools affect the outcome of a project according to at least one of the product development project characteristics described by Ulrich and Eppinger (2008); product quality, product cost, development time, development cost, and development capabilities. This means that the author assumes that changing the product develop-

ment process, or adding or removing tools for product development, will affect the project's outcome in a distinguishable (but not necessarily measurable) way. This thesis focuses on three of the characteristics: product quality, product cost, and development capabilities.

In this work, a strive for sustainability is assumed to be an integral part of product realization work and material selection. Commonly, three main aspects of sustainability are highlighted; environmental sustainability, economic sustainability, and social sustainability (The 91st United States Congress, 1969; Environmental Protection Agency, n.d.). These aspects affect product development in general (Mesa, et al., 2018), and particularly material selection since materials in products will affect environmental, economic, and societal environments. In product development literature, environmental sustainability is often discussed in terms of circularity (Shahbazi & Jönbrink, 2020). At least internally within a company, economic sustainability has been integrated into product development literature as an aspect of product development projects and specifically project evaluations (Ulrich & Eppinger, 2008). An aspect of, for example, social sustainability and its effect on product development can be seen in Hallstedt's and Isaksson's work on material criticality (Hallstedt & Isaksson, 2017). Additionally, the universal strive for sustainability has also been included in the United Nations' Global Goals (United Nations, n.d.), especially the specified goal of responsible consumption and production (United Nations, n.d.).

1.5 Limitations and delimitations

In order to create a context and boundaries for this thesis, some limitations and assumptions have been made. The significant limitations and delimitations are described here.

This work in this thesis will not cover the development of engineering materials, nor will it cover the analysis and testing of new materials. While materials will be at the center of this thesis, the work is regarding applying materials and not the development or industrialization of new ones.

The work in this thesis will center around product realization, which in this case covers product development and production. Some of the studies appended have touched upon research and development, but the author has attempted to limit the analysis to product realization-related data.

This thesis will only cover consumer products, not industrial (business to business) products. Much of the contributions might apply to the development of industrial products. However, since the scope of the research has been consumer products (where the customer is the primary user of the product during its use phase), the applicability has not been validated nor considered.

This work in this thesis will focus on product-producing companies with an existing production system. This situation means that companies have production resources that can be utilized for the new product, possibly with changes to the product and the production system. Large-scale outsourcing, or relying entirely on outside suppliers, is not considered in this thesis.

This work in this thesis will not cover software development, the inclusion of software or services into products, or the development of “smart” products. When electrical components are included in the analysis, they will be treated as a material with known quantities and behaviors.

1.6 Definitions

In order to simplify the reading of this thesis, the author has made some definitions. The author does not claim these definitions to be universal, but they are made to discuss and compare theory and observed data in this thesis.

1.6.1 Actors in the product life cycle

Within product realization or even product development, a significant amount of wildly varying work is done. While Ullman (2010) describes eleven different roles in the product design team, Ulrich and Eppinger (2008) highlight six represented company functions in their example project team, and Pahl et al. (2007) focus on tasks that the design team needs to perform to a satisfying degree within the process. In order to reduce confusion regarding work descriptions or titles, in this thesis, the author define three primary types of actors in the product life cycle: developers, makers, and users.

- Developers define the functionality and the final definition of the product, both in terms of geometry, processes, and materials
- Makers transform resources into products, ensuring that it fulfills the definition of the product set by the developers
- Users interact with the finalized product in some way

If this is translated into traditional positions, it means that designers, design engineers, and most engineers fall into the category of developers. Production engineers, production planners, machine operators, and assembly workers fall into the category of makers in much of their daily work. Users can be both primary and secondary users, as defined by how they interact with the product.

This definition also means that one employee can act as multiple actors, depending on their task or work description. These three actors should not be viewed as a direct translation of professions but rather a set of tasks thematically linked together in the product life cycle, similar to what Ullman (2010) describes in their definition.

1.6.2 Product realization

Product realization is, in this thesis, seen as the part of the product life cycle concerned with industrially developing and producing products for a market. This definition was also used in Study 5, presented by Henriksson and Dettterfelt (2018). Product realization is done after new technology is developed and before the distribution and use of the product in the market. In Figure 1, the product realization is marked as phases 3-6 of the product life cycle, with innovation management preceding it and sales and aftermarket superseding it. Product realization covers both product development and production, two fields that will be further explained in the theoretical framework in chapter 3.

Figure 1. The product life cycle, including the product realization process in the center. The figure is based on a figure previously published in study 5.

1.6.3 Production and manufacturing

In this thesis, the author will use the definition of production and manufacturing described in Henriksson (2017): production is the umbrella term for manufacturing and assembly, and manufacturing is the forming, shaping, and treatment of raw materials into components.

1.6.4 New and novel materials

New materials are defined, in this thesis, as materials that are new to the application, developer, or company. That does not imply that they are newly developed or not mature as materials. The term novel materials will be used to describe materials in a pre-industrialized or just-industrialized state, where that is needed.

The image features a white background with a decorative pattern of overlapping purple circles of various sizes in the lower half. A large, white, sans-serif number '2' is positioned in the lower right area, partially overlapping the purple circles.

2

2 Methodology

The research presented in this thesis has been generated using a multimethod approach. This approach has focused on explorative research to expand the existing knowledge regarding developing new products for consumer use. To generate this knowledge, seven studies, each described in separate papers (appendix 1-7), have been designed and performed during the duration of this work. To get a quick overview of the methodology without reading detailed descriptions of the selected methods, the author recommends the reader to focus on sections 2.1 and 2.6.

Since research on product realization to some extent relies on creativity and making of physical artefacts, it is reasonable to look at other fields incorporating these aspects. One such field is design. For research on art and design, Frayling (1993) has described a framework for different types of design research. The framework described three different types of research; **Research through design**, **Research into design**, and **Research for design**. **Research through design** can be described as studies done where design is an integral part of the research process, for example, by customizing technology to test new features (Frayling, 1993); **research into design** can be described as research on the design process or on design artifacts, for example in a historical or technical context (Frayling, 1993); and **research for design** can be described as research done to aid future design process work (Frayling, 1993).

Using this framework for research and design to describe the seven different studies appended to the thesis; studies 1 and 7 utilizes a **research through design** approach, studies 2, 4, and 6 utilizes a **research into design** approach, and studies 3 and 5 utilizes a **research for design** approach.

Studies 2 and 6 have been done observing students in research-adjacent product development projects. This means that they can be viewed from two perspectives; the perspective of the participating students, and from the observing researcher. These two perspectives affect which type of design research the work can be seen as. From the perspective of the participating students, these studies could, using Frayling's (1993) descriptions, be described as **Research through design**. To quote Frayling (1993) on what research through design can be:

“Action research – where a research diary tells, in a step-by-step way, of a practical experiment in the studios, and the resulting report aims to contextualize it. Both the diary and the report are there to communicate the results, which is what separates research from the gathering of reference materials.”

What is described in the quote above is true of some of the work in studies 2 and 6 for the participating project teams and could therefore define the work as done via **research through design** for them. However, these projects have been done by students, and the resulting reports have been used as one of multiple data sets in the author’s observational and action research case studies on how the project was done. The author has therefore defined them as **research into design** within the scope of this thesis since the author has used this viewpoint on the projects included in studies 2 and 6.

The combination of different design research approaches, using all three approaches described by Frayling (1993), was done to widen the coverage of the knowledge; the knowledge gathered in the **Research for design** and the **Research through design** studies have informed the **Research on design** studies, and vice versa.

2.1 General research process

The general research process has been highly iterative, using multiple rounds of case studies and literature reviews, as shown in Figure 2. The general process has been inspired by DRM, Design Research Methodology (Blessing & Chakrabarti, 2009), and grounded theory (Goulding, 2002). The author has continuously revised and refined the findings through several iterations, as per both DRM and grounded theory, to build the knowledge dispelled in this thesis. This iterative process has resulted in multiple uses of most methods described in this thesis, as shown in Figure 1. In this process, the author has iterated through several projects with new respondents as recommended through DRM, continuously using respondents with similar backgrounds and assumed knowledge. This iterative process has been done using industrial design engineering students as participants in multiple case studies, and combined with action research studies and interview studies. The author has not formulated any new full-scale theories in-between the iterations, as inspired by the grounded theory approach.

The methodological approach to the research in this thesis has been a multiple methods approach, combining multiple different qualitative methods built upon different scientific paradigms, inspired by Frost (2013).

The knowledge in this thesis has been built upon four methods; literature reviews, case studies, interviews, and action research. Design fiction has been added to this kappa as a methodology to further and deepen some insights. The appended studies have been using the methods described in the manner seen in Figure 2.

Figure 2. The general research process, described by the use of the research methods mentioned above throughout the research process. Multiple bars for one method mean that multiple studies using the method were done in parallel. Methods have been intersecting through the research, meaning that the methods cannot be viewed as exclusive.

These four main methods cannot be viewed as mutually exclusive; the case studies, for example, contain both action research and interviews at specific points. This does not mean, on the other hand, that all interviews have been done within case studies; there is an intersection and interconnection between these methods that have been developed throughout the research process. The four main methods for knowledge-building in this thesis will be presented in further detail through the rest of this chapter, along with descriptions of their implementation and critical reviews of the methods' strengths and weaknesses. In each section, the author will introduce the method and explain the main features as described by the academic community, and then explain how this method has been implemented in the research described in this thesis. Then, the author will present a critical review of the method in general, and highlight challenges and issues when working with said method, before discussing how these aspects have been managed in the research presented in this thesis.

2.2 Literature reviews

In general, a literature review can be used to examine state of the art in a theoretical field, and guidelines for systematic literature reviews exist in, for example, software engineering (EBSE, 2007). At least two general approaches to literature reviews can be found in methodological literature; traditional literature review as described in EBSE (2007) could be seen as a breadth-first approach, while methods such as snowballing (Wohlin, 2013) could be seen as a depth-first approach to the literature search.

The primary literature study in this thesis has been done in study 5 (further described in 4.2.5 and appendix 5), where this was done to understand what ideas of the production system are described in product development literature, especially literature used in product development courses for mechanical engineers and industrial design engineers in Swedish universities. Therefore, Pahl et al. (2007), Ulman (2010), Ulrich and Eppinger (2008), and Johannesson, Persson, and Pettersson (2013) were selected as a base for the literature study since these were known

by the authors to be used in educational contexts for mechanical engineering and industrial design engineering students in Sweden. These texts were then complemented by older sources that emphasize the integration of multiple fields into product development. To quote Henriksson and Detterfelt (2018) on how the complementary sources were selected:

“Andreasen and Hein (1986) was chosen because it is one of the oldest descriptions of the concept of Integrated Product Development (IPD) originally presented by Olsson (1985). One of the corner stones of IPD was to incorporate the production system development during product design to avoid working sequentially.

Cooper (1990) was selected because it introduced the widely used stage gate model of product development; a model that has been widely applied in industry and in research. The original model has been added by the author (Cooper, 2014) along with co-authors (Cooper & Sommer, 2016), and these have been partially included in the study.

Finally, Prasad (1996) represents one of the most widely used and referenced models that introduced the Concurrent Engineering (CE) concept for product development.”

In total, there were seven described models; Pahl et al. (2007); Ullman (2010); Ulrich and Eppinger (2008); Johannesson, Persson, and Pettersson (2013); Andreasen and Hein (1986); Cooper (Cooper, 1990; Cooper, 2014; Cooper & Sommer, 2016); and Prasad (1996). These seven models were evaluated on multiple aspects, analyzing vertical and horizontal coverage of production and production system development in product development literature (Henriksson & Detterfelt, 2018).

The more generalized literature study, used for theory building on product development and design, sustainability in product development, production system development, and decision theory, has been done with iterative studies or “sprints” rather than as a more extensive cohesive study at either end of the process. The process has been iterative, with insights from studies fueling the need for specific literature studies and findings from these literature studies fueling both case studies and further literature studies. The method used for this generalized literature study has often been a variant of the snowballing literature study method, as described by Wohlin (2013), combined with initial, broader, database searches to start each sprint. A snowballing-inspired process has also been used to find keywords and search terms within these sprints.

2.2.1 A critical review of literature reviews as a research method

In this research, literature reviews have been used to create a solid theoretical foundation both informing the setup of the data collection in the applied studies and as a framework for analyzing the data collected in the same studies. Since the other methods used focused on collecting rich, applied data, the literature reviews were selected to create a solid theoretical base.

A risk when using literature reviews to build theory is to build in publication bias in the theory; since positive results are more likely to get published than negative (EBSE, 2007), this can affect the body of literature and, therefore, the conclusions that can be drawn from a data set generated via literature review. Using a method like snowballing (Wohlin, 2013) could risk missing specific literature due to the dependency of a specific author referencing relevant literature. However, this could be argued as a weakness of the traditional systematic approach, given that there is a dependency on finding the correct search terms and performing an adequate screening to generate valuable results.

In this thesis, part of the process to mitigate blank spots or oversights in the literature review has been to iterate the work with new reviews both throughout the studies and in the analysis presented in the thesis. The rationale has been that multiple smaller sprints should create multiple starting points and should therefore decrease the risk of creating critical gaps in the literature review. This coverage, of course, comes at the cost of depth in the research (assuming a finite time allocated for the literature review), but the author has deemed the depth achieved to be satisfactory for the analysis in this thesis.

The literature reviews have been done with three alternating purposes; to build theoretical understanding, to identify gaps or questions to investigate in applied research, and to gather comparative data for comparison with data gathered through more applied methods like interviews or observations. This alternating purpose has helped the author build the body of knowledge while keeping both the theoretical knowledge and the applied studies relevant to the research scope.

The risk of recreating publication bias in the literature review parts of the thesis has been acknowledged but deemed of lower significance; in study 5, a possible publication bias would still be interesting because the publication bias would be applied in engineering education. Additionally, in the main theoretical chapter in this thesis, the theory presented is compared to empirical data from several product development projects. This approach should at least reduce the risk of having conclusions affected by publication bias, as described by EBSE (2007).

2.3 Case studies

The case study is a research method to understand complex phenomenon, on individual or group (team/organization/society) levels (Yin, 2014). Yin (2014) defines a case study as focused on contemporary events and behavior, explaining “how” and “why” rather than “what.” This means that a case study is a suitable option for understanding how multiple personal, societal, and technological factors interact in a decision-making process. The research methodology is also especially suited for “*holistic, in-depth*” research inquiries (Idowu, 2016). Yin (2014) emphasizes the definition of the unit of analysis to create boundaries for the study. Where individuals or small groups are seen as more concrete units of analysis, decisions and projects are highlighted as less concrete (Yin, 2014). Case studies including multiple cases can either compare the different cases or use them to complement each other (Yin, 2014).

In the research presented in this thesis, the case studies have typically been built around specific projects. The unit of analysis has been the design process and the decisions made by the design teams, focusing on how they have managed material aspects throughout the project and not taking the resulting product into account. Data has been gathered through observations, reoccurring interviews or supervision meetings, and project documentation written by the team members. For some of the projects, post-mortem group interviews have been done to complement the other data sources. The author has written the project briefs and acted as supervisor for student projects used in the case studies.

During the research process described in this thesis, multiple case studies have been performed. Both single-case and multiple-case studies have been done; all multiple-case studies have used the complementing method described by Yin (2014), rather than the contrasting methodology.

2.3.1 A critical review of case studies as a research method

Since the research done presented in this thesis is applied, and since early investigations showed that there is a need for something more than descriptive studies focusing on what is being done as well as deductive approaches (often with prescriptive results), case studies were deemed to be a suitable method for further understanding the current situation. The case studies have been used to explain how and why developers behave in specific ways in the product realization process, and how multiple factors interact to create specific outcomes within the studied projects.

Some of the criticism regarding case studies is centered on the issues with using qualitative methods (since case studies often use qualitative approaches). A criticism that might stem from this is the idea that knowledge from case study research is not generalizable, which has been discussed and questioned based on its relevance as criticism in earlier literature (Flyvbjerg, 2006). The challenge of using qualitative approaches also has to be weighed against the difference between analytical and statistical generalization (Yin, 2014). The use of case studies in a phenomenological manner, excluding statistical and other quantitative approaches, can risk the replicability of the research as well as the possibility for generalization.

zation. The specific setting for each case might not be replicable, and too drastic conclusions might be drawn from a too-small dataset (Idowu, 2016). On the other hand, case studies can give insights on the specific and local not possible with other methods (Flyvbjerg, 2006).

When performing case study research, there is often an overlap between data collection and analysis (Eisenhardt, 1989) that can be problematic from a confirmation bias standpoint; since some data is analyzed before all data is gathered, this initial data can be overvalued in the analysis since it affects later data collection. This thesis has applied a qualitative research approach, so no statistical generalization will be made using the data presented. In terms of replicability, most of the case studies have been done using industrial design engineering students as participants, giving more of a replicable input; the educational background and skills of the students can be described with some level of detail and consistency from project to project. Of course, there are individual variations between participating individuals and project groups, but they should be significantly lower than would be the case in the industry. Using complementary methods as described by Yin (2014), the multiple case studies have been done to generate a more extensive data set and thus avoid drawing too drastic conclusions from a narrow viewpoint. In total, over 40 different cases have contributed to the total dataset used in this thesis.

Eisenhardt's (1989) points on confirmation bias have been considered. The iterative workflow and a critical review of the data and insights throughout the research have been the primary mitigating factor. The author has also had continuous discussions with academic collaborators throughout the work in an attempt to moderate the effects of early data further. The use of published or submitted studies in the thesis can also be seen as an effort to mitigate this; since every published study has been reviewed separately, the risk for confirmation bias in each of them is lower than what would be the case if this work was done using unpublished data.

2.4 Interview studies

Interview studies use conversations to gather information from a specific respondent's point of view, especially in qualitative interviews (Kvale & Brinkmann, 2009). In qualitative research, interviews are typically used to extract narratives from respondents regarding a specific topic (Qu & Dumay, 2011). These narratives are then analyzed to generate new knowledge. An important part of the setup of an interview study is the relationship between the interviewer and the interviewee: while interviews can be understood as “*collaborative knowledge production*” (Aarsand & Aarsand, 2019), the asymmetry of power between interviewer and interviewee cannot be neglected (Qu & Dumay, 2011).

Interviews in research can have at least two different goals that will affect how the interviews are designed. Broadly, the interview can be seen as both knowledge production (Aarsand & Aarsand, 2019; Kvale & Brinkmann, 2009), where the participants collaboratively exchange ideas and reframe the issue and create parts of the knowledge disseminated in the interviews during the interviews themselves, and knowledge collection (Kvale & Brinkmann, 2009) where the interviewer attempts to unravel the knowledge “hidden” in the interviewee’s experience and answers.

In this thesis, two different types of interviews have been used in the studies; one-on-one interviews (inspired by Adams, (2015)) with industry representatives, and focus group interviews with student teams similar (but with some changes) to Nyumba et al.’s (2018) description of focus group discussions. The one-on-one interviews in this thesis have been done in a semi-structured manner, as described by Adams (2015), while the focus group interviews have been done in an unstructured or close to unstructured manner. In this thesis, the one-on-one interviews have been done as single interviews, while many of the focus group interviews have been done in reoccurring series of interviews. The one-on-one interviews were done as telephone interviews, while focus group interviews were typically performed in person. As shown in Figure 3, the design process for the one-on-one interview study was iterative, using both external (with industry representatives) and internal (with academic representatives role-playing industry respondents) test interviews. These were done to develop the interview manuscript, and anticipate possible responses in order to prepare follow-up questions. The one-on-one interviews with industry representatives have approximately followed Kvale and Brinkmann’s miner metaphor (Kvale & Brinkmann, 2009), attempting to extract specific knowledge

Figure 3. One-on-one interview study design process.

from the responses and narratives given by the respondents. The data from the test interviews, both internal and external, has not been included in the interview data set to avoid closed circle data collection. For further inquiry into the one-on-one interviews, go to 4.2.4 or appendix 4.

The focus group interviews with student teams have been done as a part of larger case studies, with unstructured reoccurring supervision meetings and end-of-project debriefing sessions. These have been done as unstructured interviews with all participants in one room, and the author taking brief notes asking about the current status of projects, possible bottlenecks, and/or identified risks, attempting to become more of a moderator for a discussion between students rather than an interviewer in the end-of-project debriefing sessions similarly to how Nyumba et al. (2018) describes focus group interviews. Both types of focus group interviews, especially the reoccurring supervision meetings, have followed Kvale and Brinkmann's traveler metaphor (Kvale & Brinkmann, 2009), attempting to create knowledge in collaboration with the respondents.

2.4.1 A critical review of interviews as a research method

Interviews were used in this research to complement both other data within the student team-driven cases and to gather applied data from industrial representatives. The case studies on student projects were otherwise driven by observations and documentation from the participants, and interviews were used as a way to get tangential information as well as a way to create communication with the participants. In the interviews with the industry representatives, the focus was on extracting information not documented in written form or described in more theoretical models from academic literature.

Interviews should be taken as one respondent's communicated view of the topic and not absolute or objective truth (Qu & Dumay, 2011). Since face-to-face interviews are time-consuming (Gillham, 2000; Adams, 2015), telephone interviews can be viewed as an alternative to reduce some of the time and costs for logistics associated with face-to-face interviews. On the other hand, this setup loses some of the quality that can be found in a face-to-face interview (Gillham, 2000), with the removal of facial expressions as a medium for the interviewer to understand the respondent and adjust the interview accordingly. Telephone interviews are harder and more challenging to do well than face-to-face interviews (Gillham, 2000) but can be a necessary solution in some circumstances. Using visualization tools in interviews has shown promise in, for example, enhancing the data (Glegg, 2019), but this is not possible with a traditional telephone interview; this is another drawback when performing telephone interviews as a replacement for face-to-face interviews.

While study 4 is based on the interview respondents from industry representatives and thus relies heavily upon these results, there has still been a comparison with existing theory on subject matters. In other studies, interviews have been used

as complementary information and not a single source. Both of these things have been done to not rely solely on interview data, given that the respondents' answers cannot be seen as an absolute truth (Qu & Dumay, 2011). Also, in the final analysis, interview data has informed the analysis rather than being used as absolute fact. If theory and interview results differ, it has been noted as interesting, but this has not been deemed enough to discard said theory as a whole.

In this thesis, telephone interviews with industry representatives were used to enable contacts with interviewees not otherwise possible (due to time constraints, traveling, and social distancing recommendations during 2020). While the author acknowledges that this can have had a detrimental effect on the outcome of the interviews, the possibility of interviewing these respondents was deemed to have a higher impact even if the individual interviews have been less dense in data. The quality loss in the interviews was assumed to be stochastic and should not significantly affect the outcome.

The focus group interviews with students in this thesis were done face-to-face, due to the barriers of time and travelling being much smaller when working with students on-campus. In these cases, the upsides of face-to-face interviews were deemed to outweigh the possible convenience of telephone interviews.

2.5 Action research

Action research has been used in social sciences since the 1950s (Ottosson, 2003), exploiting a shortcoming of classical reductionistic research methods derived from natural sciences. While parts of the foundation for action research come from a positivist paradigm, other ideas like critical theory have been included and have had a significant impact on action research as a method for theory building (Willis & Edwards, 2014). Instead of classical, observational, or reductionist methods, action research can be described as a way of joint learning between the researcher and the research objects (Ottosson, 2003). In management research, this has been described as combining the role of the academic researcher and the management consultant (Gummesson, 2000). In educational settings, action research is tightly connected to practice and improvement via research-derived techniques rather than generalized theory (Ferrance, n.d.; Somekh, 2005). Another critical point in action research is to generate real-life transformative change (Rowell, et al., 2015).

Participation action research is a form of action research where the researcher affects the research environment and actively participates in the studied environment (Ottosson, 2003). Ottosson (2003) distinguishes participation action research from participatory action research by claiming that participation action research actively seeks to improve methods and concepts, something participatory action research does not necessarily do. Participatory action research, instead, focuses on understanding processes and social structures (Whyte, 1991).

In studies 2 and 6 presented in this thesis (for further information on the studies, please go to 4.2.2 and 4.2.6 or see appendix 2 and 6, respectively), the author has acted as a supervisor in student course projects, utilizing an action research-inspired approach. This meant that the author was not working actively as a developer within the projects included in the studies but was continuously updated on progress and challenges. The author introduced some changes within projects and updated project briefs and supervision routines between projects, based on the experiences from the practice of supervising active development projects. This process meant that the author and the participants in the student course projects, to some extent, jointly developed the briefs and project setups by examining progress throughout the projects. These projects were open-ended, and the author exercised authority to change project scope and delimitation if this framework, in collaboration with the participating students, was deemed unsuitable. In study 7 (further explained in 4.2.7 and appendix 7), on the other hand, the author was actively participating in one project as project coordinator and in two as a participant, utilizing a participation action research approach. This meant that the author was integrated into the organization performing the project, being on site three to four days per week during the duration of the project, and working actively as a project coordinator setting up meetings, conducting interviews, and delivering research and development insights to recipients within the organization. All of this data, alongside communication and bi-weekly briefings with colleagues in academia and two deep-dive, unstructured interviews with the author as an interviewee, was used as the basis for the analysis done in collaboration with the co-authors of Henriksson, et al. (2020).

2.5.1 A critical review of action research as a research method

Action research was used in this thesis to ground the researcher in the topic further, as well as give further insights into the challenges faced in the product realization process, and understanding of what happens in a product realization setting when changes are made to the product, process, or people.

A substantial critique on participation action research in particular, and action research in general, is the risk for confirmation bias. While there is always a risk for confirmation bias in research, having the researcher actively participate in the process they are studying introduces new opportunities for bias. The researcher can both endure a sampling bias as well as acting in a way that encourages specific outcomes and thus creating a bias in how the case is unfolding. Action research and participation action research can also be done with too much focus on relevance and not enough focus on scientific rigor to make the research reliable (Argyris & Schön, 1991).

In this thesis, the author has attempted to manage confirmation bias by including multiple sources of information, not only relying on action research as the sole research method. If information from different sources has contradicted each other, a critical evaluation of the action research material has been conducted. In addition, the action research material has been gathered in situations where the author has had different levels of authority; projects with junior and senior students in studies 2 and 6, and projects where the author has been immersed in an industrial environment as a coordinator among senior engineers and experts in study 7. The balance of managing relevance and reliability in research, as described by Argyris and Schön (1991), has been managed similarly to how confirmation bias has been managed.

2.6 General methodological reflections

The research in this thesis has been done with a simplified hermeneutic approach, focusing on holistic theory building and acknowledging both the role of intuitive reasoning and the role of the researcher in the research. With this research approach, the preexisting knowledge and expertise of the researcher can be considered a positive, as described by Andersson (2021). Furthermore, the ability to interpret a phenomenon does require a thorough understanding of the phenomenon itself (Heidegger, 1962). This fact suggests that preexisting knowledge is not only positive but a necessity for reasonable interpretation and scientific contribution. The concept of the hermeneutic circle (The Stanford Encyclopedia of Philosophy, n.d.) does, to some extent, solidify this idea of the necessity of understanding the phenomenon in order to be able to observe it fully. To do the opposite, i.e., to study phenomena of which you have little to no prior knowledge, could be seen as a form of epistemic trespassing (Ballantyne, 2018), which is a constant challenge when performing any form of cross-disciplinary research.

Nevertheless, there is an argument to be made on the risks of a researcher being too well-grounded: could there be a risk that the researcher becomes too influenced by their preconceived notions, possibly generated by societal and cultural ideas of certain phenomena, and reproduces the narratives built into the established literature and trends? Can expert knowledge cloud the new possible insights due to cultural and educational influence? This should, at least, be discussed when working with hermeneutic research.

A possible way to mitigate this could be to, to some extent, incorporate some concepts from critical theory, like domination and alienation, as they are described by Morrow and Brown (1994). While critical theory in its purest sense might not be applicable for this type of research, the ideas of liberation and creating a better world for all human beings (Horkheimer, 2002) does intersect with the intended purpose of this thesis, as well as the focus on social interactions and human interaction that started the critical approach to social sciences (Morrow & Brown, 1994). Since social life can be argued to be distinctly different from technological or physical sciences (Morrow & Brown, 1994), the positivistic approach often used in these fields is perhaps not best suited for research understanding social life. Critical theory is an attempt at combining positivist and humanist perspectives in research (Morrow & Brown, 1994). In this thesis, the critical approach has been interpreted as questioning the normative status of established paradigms and an attempt at including more humanistic and relativistic ideas in a field that otherwise might lean towards positivistic approaches. In specific, it has resulted in a critical standpoint when analyzing new data to avoid reproducing existing narratives while still using the preexisting knowledge that the author has.

In the work presented in this thesis, the author has worked in different roles in different studies; as a developer, as an investigator, as a development coordinator, as an observer, and as a teacher. This approach has emphasized different preexisting knowledge in different situations and has been considered a possible way to mitigate the risk of only reproducing or filling in existing narratives. While there are overlaps in what preexisting knowledge could be considered valuable and/or para-

digm-reinforcing, the mindset change still has affected the outlook on the research process. Table 1 summarizes the different studies and how the author’s role has changed between studied.

Table 1. Summary of the studies appended to the thesis, highlighting the role of the researcher along with who could be considered developers in the studies and whether or not the study was done with industrial collaboration.

Study	Researcher’s role	Developers	Industrial collaboration
1	Developer	Author	No
2	Teacher and observer	Students	Limited
3	Investigator	None	No
4	Investigator	Industry	Large
5	Investigator	None	No
6	Developer, development coordinator, and teacher	Author, students, and industry	Large
7	Development coordinator and observer	Industry	Large

The research in this thesis is based on qualitative methodologies due to a combination of reasons. Firstly, the research approach was explorative, meaning that the collected data and analysis have formed future research. This explorative approach does not exclude quantitative methods, but qualitative methods are generally more suited to the explorative aspects of research. The collected data has been rich but covering relatively few projects, suggesting that a qualitative approach would suit the data better than a quantitative approach. If a quantitative approach had been used, there could have been reasons to question the reliability and generalizability of the analysis. The collected data was also broad in its coverage. Combined with the previous point, a quantitative approach would have required significantly more data collection or a smaller coverage in the analysis. This, in combination with the author aiming to produce a holistic analysis and picture of product realization, pointed towards using qualitative methods rather than quantitative.

The multiple studies appended to this thesis have contributed to different types of knowledge, both in different parts of the product realization process and how applied the knowledge is. There is also a difference in the size of the datasets since some studies are small and focused while others are multiple-case studies with broader, larger datasets. An attempt at visualizing this has been made in Figure 4. The coloring scheme used to denote each study in Figure 4 will be continuous throughout the thesis.

Figure 4. Studies in the thesis plotted on a level of application/placement in the product realization graph, the center point depicting its position. The diameter of the rings is depicting the relative size of the corresponding data set.

3

3 Theoretical framework

In this chapter, the theoretical framework is presented. This theoretical framework is the one on which the analysis of the collected empirical data will be based, bringing viewpoints from both academic and industrial research into the analysis. The theory on product development, design, and production system development has been continuously present during the studies presented in this thesis. During these studies, a gap in the theory was identified, and ideas from philosophy, psychology, and management is added to this theoretical framework fill this gap. Due to the multidisciplinary nature of this thesis, three main theoretical topics will be presented:

1. Product development and design
2. Production system development
3. Decision theory

Within these topics, further sections delves into specific topics and fields relevant to this thesis. Product development and design are presented first in this chapter since this field can be seen as the core of the thesis. Production system development is presented as the second subchapter, finalizing the traditional theoretical coverage in a product realization-related research presentation due to the chronological order of activities within product realization. Finally, decision theory is added to understand one of the main activities in product realization: decision-making.

3.1 Product development and design

In general, product development is seen as the process of defining a product to be manufactured and sold to a customer/user. Product development can be seen as the activities an organization does between a market opportunity is found, and the product is ready for the market to buy and use (Ulrich & Eppinger, 2008). One way of defining product development is *“the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale”* (Krishnan & Ulrich, 2001), which is the definition that will be used in this thesis. A part of this transformation requires the definition of the product itself (Ullman, 2010). Thus, the product’s physical, functional, and emotional design can be viewed as an activity with the product development process (Krishnan & Ulrich, 2001).

Two main philosophies have been used to discuss how new products are developed; these are commonly referred to as “market-pull” and “technology-push.” Market-pull product development means identifying problems that customers and users might have and find the best possible solution for these problems in the form of a product (Open University, n.d.). In contrast, technology-push product development is typically based on technology development; technology that, after it is developed and the properties of the technology are discovered, gets applied to a specific problem that customers and users might experience (Open University, n.d.). These two descriptions can be connected to problem-focused product development (as described by Ulrich & Eppinger (2008)), and innovation (as described by ISO (2020)), where market-pull is connected to problem-focused product development and technology-push product development is more closely connected to innovation.

Figure 5. The relationship between functional solutions from all three product manipulators. Adapted from (Ullman, 2010). A version of this was previously published in study 3.

Traditionally, the problem-focused approach has been the more common approach for academic work on product development (Ulrich & Eppinger, 2008). An innovation-related, or technology-push-inspired, methodology for designing products

relevant to this thesis is Material Driven Design, MDD (Karana, et al., 2015). MDD is material-centered; finding an application for the material in a product rather than creating a product to solve a problem and then “dressing” this product in a material as a part of the product definition process (Karana, et al., 2015).

Independently of the starting point of a product development project, three fundamental elements are possible to change in the definition of a product: geometry, material, and process (Ullman, 2010). These three factors will define the product’s appearance and functionality, and the geometry and material will be what the user interacts with when using the product. Applying this to the developer’s work means that all developer’s intent needs to be expressed through these three elements. This can be seen in Figure 5, with Ullman’s “triangular scale” being exchanged for a Venn diagram where the product solution space is the overlap between all three manipulator solution spaces.

3.1.1 Product development processes

Developing products and how this process should be defined has been a research topic since at least the middle of the 20th century with early adopters in the US, UK, and Germany (Cross, 1993; Jänsch & Birkhofer, 2006). The product development process itself has been described in many different ways; Saren (1984) has described multiple different classes of product development process models based on what is driving the progression through the process. Ulrich and Eppinger (2008) describe the product development process as a process with six phases, from planning (phase 0) to production ramp-up (phase 5), while French (1998) describes four phases with decision-points dividing them and Cooper (1990) describes five stages with the last being “*full product and market launch.*”

When looking at the work done within the product development process, it can be roughly divided into a divergent part (aiming at defining the project scope and exploring the solution space) and a convergent part (aiming at reducing the number of viable options until the best possible solution is defined), before a final solution is selected and fully defined (British Design Council, 2005; Ulrich & Eppinger, 2008; Ullman, 2010). The Design Council (2005) has envisioned two divergent and two convergent workflows in a project, while Ulrich and Eppinger (Ulrich & Eppinger, 2008) describes one divergent and one convergent workflow. The difference in how many divergent and convergent phases are described is due to different ascribed start and end points of a product development project. The differences between product development process descriptions, both in general set up and in how many phases the work is divided into, can be seen as examples of different opinions on where a design or product development starts or ends. This has resulted in multiple different descriptions of project start and end points (Henriksson & Detterfelt, 2018). Despite all this, almost all descriptions start with the formulation of the problem and end with a finished product, whether it be in a quantity of one, large-scale production, or delivery to retailers (Andreasen & Hein, 1986; Krishnan & Ulrich, 2001; British Design Council, 2005; Ulrich & Eppinger, 2008). It should be mentioned that there are exceptions where, for example, Cooper (1990) describes the starting point of a project as after a product idea is selected.

3.1.2 Integrated product and production development

To eliminate the sequential development process that has been used traditionally, sometimes referred to as “*over-the-wall engineering*” (Owens & Cooper, 2001), different ways of restructuring the process and integrating it with other necessary activities (for example, production system development) have been proposed and implemented (with varying degrees of success). In the 1980s, Andreassen and Hein (1986) defined integrated product development to bridge the gap between product development and production. Production is of particular interest to integrate with product development due to the multiple interfaces between the two processes (Dekkers, et al., 2013). In the 1990s, the term “concurrent engineering” was coined to explain a new way of developing products (Prasad, 1996). Concurrent engineering focuses on the interconnectivity of multiple different systems needed for product realization (development processes, development tools, organization, product functionality and geometry, production system, etc.) to be successful (Prasad, 1996; Koufteros, et al., 2001). In later years, concepts like systems engineering (INCOSE, n.d.; NASA, n.d.) have emerged, and the ideas mentioned earlier regarding integrating multiple transdisciplinary aspects in the product development process can be argued to be included in systems engineering.

3.1.3 Decision-making in product development

Multiple decisions must be made within a product development project before the product is fully defined (Krishnan & Ulrich, 2001). While these decisions traditionally have been described as a linear sequence, there are arguments that this is both implausible and inefficient as a strategy (Krishnan & Ulrich, 2001). Instead of this linear and sequential thinking, some form of holistic decision-making structure should be implemented to maximize the possible outcome of the available resources (Rahatulain & Qureshi, 2019). In general, an argument can be made that the academic research on product development decision-making has not been applied enough to consider real-life practice, from concept development to production planning via industrial design (Krishnan & Ulrich, 2001).

One of the challenges for decision-making in product development is what is sometimes called the design paradox; that knowledge increase and decision freedom decrease as a project progress (Ullman, 2010). This paradox means that there is an inherent conflict between knowledge and decision freedom in product development. This uncertainty is not a problem in itself but becomes a risk when combined with the stakes involved in, for example, significant investments and should therefore be avoided (Brunsson, 1980). In order to reduce the level of uncertainty, there are multiple different tools for supporting decision-making in product development (Seram, 2013), among others Quality Function Deployment (QFD) (Norell, 1992; Ullman, 2010) and Computer-Aided Design (CAD) (Norell, 1992; Henriksson & Johansen, 2015). Another way of reducing uncertainty is to work with cross-functional and stable (to a certain extent) product development teams (Slotegraaf & Atuahene-Gima, 2011).

3.1.4 Material selection in product development

Given that material is one of the main product elements, it should come as no surprise that material selection in product development has been covered extensively. In academic literature, many different aspects of material selection have been highlighted. Some worth mentioning are technical aspects (Ashby, 2005; Wu & Liu, 2014), material perception and meaning (Karana, 2009; Karana, et al., 2010), criticality and material sourcing (Hallstedt & Isaksson, 2017), and cost (Johnson & Kirchain, 2009; Hagnell, et al., 2020). Some models not explicitly designated to material selection also cover material selection in some form, sometimes tightly connected to other aspects such as production processes (Boothroyd, et al., 2010).

Many established material selection methods follow an analytical approach to select a final material candidate (Karana, 2009). This analytical focus can be expressed in the form of knowledge-based approaches (Porsch, et al., 2019), simulation-based approaches (Wu & Liu, 2014; Cho, et al., 2014), or more classical analytical approaches (Elber & Davidson, 1973; Xia, et al., 2014). In some cases, this focus on quantified data is combined with an optimization focus (Karande & Chakraborty, 2012; Vierhout, et al., 2019; Gafarov, et al., 2020). One of the more universally known analytical methods or processes for material selection is the Ashby method (Ashby, 2005). The Ashby method (Ashby, 2005) for selecting materials in mechanical design defines four steps as shown in Figure 6: Translating material requirements, screening using the constraints, ranking using objectives, and finally seeking supporting information. This basic structure can be found in other material selection processes as well (Veelaert, et al., 2016).

Figure 6. Ashby’s method for material selection.

The first step, translating material requirements, means taking the functions and constraints affecting the final product and translating them into material requirements. In this step, ranked objectives are also distilled from the description of functions and constraints (Ashby, 2005). If we imagine designing a stool and looking at this step, the function could be to support the load of a user sitting on the stool, one of the constraints could be the temperature span in a standard house, and the objective is to make it as light as possible.

When the translation is done, the developer screens for material candidates using the constraints and functions as requirements (Ashby, 2005). In the example of designing a stool, we can exclude materials that are not in solid form at room

temperature and materials that do not have the structural rigidity to hold up the mechanical load of a grown human within our maximum allowed volume for the product.

When a set of viable material candidates are available, a ranking of these materials can be done (Ashby, 2005). If the objective is to minimize weight, the ranking should be a ranking of which materials could result in the lightest end product. This objective might be translated into specific stiffness.

When the ranking is finished, supporting information can be sought after. This supporting information is often non-quantifiable and might include local conditions (Ashby, 2005). Does the company have a preferred supplier or in-house expertise in some materials, or have the customers expressed a preference for a type of material expression?

The Ashby method does not explicitly cover topics like meaning or perception of materials, and this is a common feature of the analytical material selection methods. Instead, practicing designers have developed their own personal methods or used intuitive reasoning to incorporate the emotional aspects in material selection (Karana, 2009; Asbjörn Sørensen, et al., 2017). The same goes for architects when considering materials for buildings (Wastiels & Wouters, 2012). Furthermore, while there are different information needs throughout the product realization process, there is a need for integration between tangible and intangible material properties (Veelaert, et al., 2016; Piselli, et al., 2018). While there are some patterns in how people perceive materials, for example, calming effects of wood surfaces, multiple different material properties combine to create these effects (Jalilzadehazhari & Johansson, 2019). Material experience is also context-dependent (Wastiels, et al., 2012), complicating this process further for developers.

Material selection cannot only be viewed in solitude, either, as material selection often is intertwined with other aspects of the product realization process (Asbjörn Sørensen, et al., 2017). The product's mechanical engineering-related properties (Hagnell, et al., 2020) and production properties (Johnson & Kirchain, 2009) are two aspects that bridge the gap between material selection and other parts of the process.

3.1.5 Material diversification in product development

Materials, raw, composites, or alloys, are what make physical artifacts and products. Material is one of the fundamental elements for changing a product (as mentioned previously), be it in performance, cost, or perception (Karana, 2009). Like in the automotive industry example shown in Figure 7, some industries have seen a rise in material differentiation (Henriksson, 2017). This differentiation can be divided into two different trends; the introduction of new materials and material diversification within a product. As late as 2017, the automotive industry had not yet converged on how and where new materials were best introduced in an automotive body (to replace steel), something that has generated multiple different solutions in different product-producing companies (Henriksson, 2017).

Figure 7. Material distribution (in %) of an average American car by year (figure from Henriksson, 2017).

Some current material trends worth noting are the increased use of technologically advanced, biologically sourced materials, the emerge of nano-, “smart” or active materials, and novel composites. Wood-based materials are mentioned

explicitly as possibly replacing some of the fossil-based polymer materials in use today (Kääriäinen & Rueda Mejía, 2020), and research is being done on the use of, for example, mycelium-based materials that could enable the possibility to “grow” products (Pasold, 2020), while “smart” materials can bring the possibility to create shape-shifting materials (Gardan, 2019).

Bio composites have been introduced among other materials, and their usage has grown as the emphasis on sustainability has been increased (Faruk, et al., 2012). Several industrial implementations of different bio composite materials could be seen in the automotive industry between the late 1990s and the early 2010s (Koronis, et al., 2013).

Since different industrially developed materials have significantly different physical properties (Hosford, 2008; Koronis, et al., 2013; Henriksson, 2017), materials will respond differently to production system behavior and environments (Tempelman, et al., 2015; Henriksson, 2017). Examples of this are differences in behavior when exposed to an outside force and how the material behaves in different temperatures (Henriksson, 2017).

3.1.6 Summarizing product development in this thesis

Product development is a field covering the definition of the product that should be produced and sold to customers. Within this field, the process of defining the product and making decisions have been covered in different forms for over half a century by now. Many different proposals for managing the product development process have been given, and the need for interdisciplinarity has been highlighted as early as in the 1980s with Andreasen’s and Hein’s work on Integrated Product Development (Andreasen & Hein, 1986). Therefore, the challenge of integrating many disciplines and objectives is not a new concept but has not yet been fully resolved. Adding to that challenge, a mechanistic and programmatic view on the product development process is expressed in much of the existing literature and a view of decision-making in product development as linear and sequential as described by Krishnan and Ulrich (2001).

3.2 Production system development

In this thesis, production is understood as the industrial making of discrete, physical artifacts, according to a defined plan. Production can be divided into manufacturing and assembly, which can themselves be broken down into subsets of activities. This division is shown in Figure 8, which is based on an earlier figure from the author (Henriksson, 2017). These activities are often research topics themselves. Two examples of separate and thriving research fields are additive methods (Wiberg, 2019; Chen, et al., 2020) and cutting (Pan, et al., 2001; Königs & Brecher, 2018), two fields that have expanded to include topics as diverse as workplace safety, product design, optimization, and statistics. However, this thesis will not cover these activities in any detailed sense. Instead, production will be covered on a holistic and more abstract level.

The development of the production system is an integral part of the product realization process (Bellgran & Säfsten, 2010). It is sometimes included in what is traditionally called the industrialization process (Wlazlak, 2019), but production

should always be taken into account early in the product design process for the best possible result since this reduces cost (Boothroyd, et al., 2010). The general process for production development has traditionally been very similar to linear product development with a pre-study, followed by planning, design, acquisition/production, testing, and installation before implementation (Bellgran & Säfssten, 2010). However, it could also be argued that there is an organizational side to production development (Toledo, et al., 2019). The main reason for changing the production system is usually tied to introducing new, or planned, products that cannot be produced within the current system (Bellgran & Säfssten, 2010). However, other reasons such as capacity improvement (Bellgran & Säfssten, 2010) or working environment changes (Neumann, et al., 2009) also exist in the literature.

Figure 8. Production and its underlying subsets, adapted from (Henriksson, 2017) with added subsets from (Boothroyd, et al., 2010)

One way of reducing the need for extensive production system development, would be to reduce the need for external initiation of production system change (Bellgran & Säfssten, 2010). This reduction could be done by building flexibility into the production system to manage changes within the bandwidth of the existing system.

3.2.1 Production flexibility

As a general concept, flexibility can be described as a capability of multiple different responses to different inputs from the company's environment (Phillips & Tulandhar, 2000). When applied to production, these new inputs can be anything from order sizes to legal requirements or material prices. One example is the increase of part numbers (different components) in the German automotive industry, which went up by 400% in the 15 years between 1975 and 1990 (Wiendahl & Scholtissek, 1994); a change in material and component handling that increases demands on flexible manufacturing systems since as much as 50% of available components made up less than 5% of the total production (possibly due to being parts in optional systems selling in small numbers). Zhang et al. (2003) define manufacturing flexibility as *"the ability of the firm to manage manufacturing resources and uncertainty to meet customer requirements."*

This ability to manage uncertainty generally comes at the cost of efficiency (Phillips & Tulandhar, 2000), which means that superfluous flexibility might hurt a company financially. Thus, companies should try to minimize the manufacturing flexibility to only what is needed, the need being due to multiple different internal and external factors. Different types of production-related uncertainty, such as order sizes, material prices, the introduction of new materials, or product variations, also require different types of flexibility (Beach, et al., 2000). In order to understand and simplify this from one complex measurement, several authors have tried to classify and define manufacturing flexibility in different subsets that can be viewed, measured and sometimes managed individually (Gerwin, 1987; Gupta & Goyal, 1989; Beach, et al., 2000; Zhang, et al., 2003).

In contrast to Phillips and Tulandhar, Gerwin (1993) proposes another view on flexibility; as a resource and investment rather than a cost. While this approach has merits, and a discussion on the concept of cost as a driver for decisions in product realization is intriguing, even in the examples put forward by the author in the paper, it could be argued that this "flexibility investment" could be seen as a cost for the investment of market shares or added customer value. Therefore, Gerwin's model of flexibility as an investment has been viewed as outside the delimitations of this work and is not further analyzed in the thesis.

For companies manufacturing customer products, customer satisfaction is a possible measure to evaluate the current process and product portfolio. Customer satisfaction has been described as the degree to which customers perceive that the products they have bought are worth more than the price the customer paid (Tracey, 1996, in Zhang, et al., 2003). Zhang et al. (2003) also showed the relationship between manufacturing flexibility and customer satisfaction.

As mentioned earlier, several authors have attempted to classify manufacturing flexibility in multiple subsets, each possible to quantify and “measure” in some way. Some of these attempts can be seen in Table 2. Browne et al. (1984) defined eight different types of flexibility, a taxonomy that was further developed by both Gupta and Goyal (1989) as well as Sethi and Sethi (1990). Gerwin provided an alternative during the same period (Gerwin, 1987), while Zhang et al. updated the paradigm by highlighting flexible manufacturing competencies (Zhang, et al., 2003) rather than types of flexibility.

Zhang et al. (2003) also expand on Upton’s classification of manufacturing flexibility in two main categories: internal competencies and external capabilities. Internal competencies are explained as what the company can do, while external capabilities are dependent on what the customer perceives. This capability-centered view is another way of looking at types of flexibility but can be applied to all earlier classifications of flexibility.

The different classifications of flexibility seen in Table 2 are generally quite similar; there is an emphasis on managing differences in production workload, how operations are sequenced in the process, in the products being made, and in the input. This is also reflected in the flexible manufacturing competencies that Zhang et al. (2003) describes. These generalized classes of flexibility can be broadly divided into two categories; characteristics affecting the possibility of effectively making a new product within the system, and characteristics affecting the possibility of effectively switching between different products at the same production line. The first set of characteristics is directly connected to introducing a new product and new components, where material change is an (perhaps amplified) example. The second set of characteristics are intimately connected to mixed model-production and multi-product production lines. This is connected to material diversification and thus relevant for other aspects of material introduction. In this thesis, managing differences in products and input are the most relevant aspects of production flexibility since they are most closely connected to material management and handling.

Suppose multiple materials will be in the production system (new materials are introduced without eliminating existing materials). In that case, aspects like sequencing, routing, and mix flexibility can become necessary flexibility measures for the company. This is especially true if the production system is of mixed-model variety, and thus setup time will be vital for maximum production volumes.

According to Gerwin’s (1987) model, material and sequencing flexibility are most affected by material diversification. Rerouting and mix flexibility could be indirectly affected, depending on the combination of materials and products used in the production line, especially so if mixed-model assembly lines are used.

According to Gupta and Goyal’s (1989) classification, process sequence flexibility can be directly affected, while machine, product, and routing flexibility comes into account when using mixed-model assembly lines, more or less the same as Gerwin (1987).

Table 2. Classifications of manufacturing flexibility, in order of mentioning in the respective sources.

Browne et al. (1984)	Gerwin (1987)	Gupta and Goyal (1989)	Sethi and Sethi (1990)	Zhang et al. (2003)
Machine flexibility	Mix flexibility	Machine flexibility	Machine flexibility	Machine flexibility
Process flexibility	Changeover flexibility	Process flexibility	Process flexibility	Labor flexibility
Product flexibility	Modification flexibility	Product flexibility	Product flexibility	Material handling flexibility
Routing flexibility	Rerouting flexibility	Routing flexibility	Routing flexibility	Routing flexibility
Volume flexibility	Volume flexibility	Volume flexibility	Volume flexibility	Volume flexibility
Expansion flexibility	Material flexibility	Expansion flexibility	Expansion flexibility	Mix flexibility
Operation flexibility	Sequencing flexibility	Process sequence flexibility	Operation flexibility	
Production flexibility		Production flexibility	Production flexibility	
			Material handling flexibility	
			Program flexibility	
			Market flexibility	

Out of Sethi and Sethi's (1990) additional characteristics, program and market flexibility can be related to material change. Program flexibility could be seen as restricting new material introduction; it focuses on short lead times between products (something that discourages material differentiation). Market flexibility would be positively affected by material flexibility since new materials can be introduced to respond to new market demands. The intuitively most interesting flexibility characteristic for this thesis, material handling flexibility, is defined as the *“ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves”* (Sethi & Sethi, 1990). Thus, this is focused on managing material flow rather than addressing mixed materials or multi-material components.

Looking at Zhang et al.'s (2003) flexible manufacturing competencies, machine, labor, routing, and mix flexibility could be seen as affecting the introduction of new materials. These characteristics deal explicitly with the difference between two products and thus will both be affected and affect material diversification or the introduction of new materials, assuming that introduction of new materials will change the definition of the product in terms of geometry and composition.

Materials clearly affect the need for flexibility (as can be derived from the above analysis of flexibility characteristics and their relationship to the introduction of new materials), but quantifying the exact effects on a general level is a complicated task. What can be said is that diversification in materials used in a production system possibly increases the demands on the system itself. Due to the different properties of the materials, different joining methods can become necessary. These different joining methods can affect tact time due to their curing/cooling time (Henriksson, 2017). The difference in tact time can result in a need for sequencing flexibility, especially if multiple products are manufactured within the same production system. The different material properties can also affect the need for machine flexibility: the forces needed to mill polymers are (in general) significantly lower than the forces needed for steel, and thus the machinery needs to be able to adapt if polymer and steel milling will be done in the same machinery.

3.2.2 Summarizing production development in this thesis

The topic of production is vital for understanding and succeeding in bringing products to market. Production development can give insights into how the production system can be developed to produce a specific product, and production flexibility can tell us how the production system can be made robust enough to manage uncertainties and future changes without requiring a total redesign. This robustness can reduce the need for production system reconfigurations since some changes in inputs or expected outputs can be managed within the existing system design. When looking at how the material affects flexibility, some aspects are more clearly affected. The effects of materials are evident in a material diversification strategy, where many different materials with different properties are managed in the same production system.

3.3 Decision theory and analysis

A decision can be defined as a choice between different options to enable a desirable outcome (Eilon, 1969). Decision theory is the theory of decisions, or as defined by Hansson (2005), the theory of “*goal-directed behavior in the presence of options*.” The presence of options is central to decision-making, either between different alternates or between doing or not doing something, which has also been covered in product development literature (Derelöv, 2009).

3.3.1 Normative and descriptive decision theory

There are two schools of thought in decision theory, normative and descriptive theory. Normative decision theory covers a theoretical or logical optimum, “*how people ought to behave in given decision situations*” (Rapoport, 1998), while descriptive decision theory covers how people make decisions in reality (Rapoport, 1998).

Normative decision theory, as mentioned previously, covers how people should be making decisions (MacCrimmon, 1968; Rapoport, 1998; Suhonen, 2007). This means that it is centered around logical reasoning and a mathematical language (Rapoport, 1998) and that rational decision-making is a goal when trying to implement a normative decision theory (Suhonen, 2007).

Descriptive decision theory is concerned with how people make decisions in real life (Rapoport, 1998; Suhonen, 2007) and tries to create models and explanations of experimental data rather than start with a set of assumptions (Suhonen, 2007). This means that descriptive decision theory aims to explain the decision-maker’s values, beliefs, and behaviors (Slovic, et al., 1977) and that concepts like ambiguity are central to descriptive decision theory (March, 1994).

Both normative and descriptive decision theory can be falsified, to quote Hansson (2005):

(F1) A decision theory is falsified as a descriptive theory if a decision problem can be found in which most human subjects perform in contradiction to the theory.

/.../

(F2) A decision theory is weakly falsified as a normative theory if a decision problem can be found in which an agent can perform in contradiction with the theory without being irrational.

(F3) A decision theory is strictly falsified as a normative theory if a decision problem can be found in which an agent who performs in accordance with the theory cannot be a rational agent.

As shown, the falsification of normative decision theory heavily revolves around the concept of rationality and whether rational decisions can be made.

3.3.2 Rationality in decision-making

Rationality, as it is used in this thesis, is an attribute of a decision-making process. A rational decision-making process only follows when the participants have fully examined four central questions (March, 1994):

1. What alternatives are possible?
2. What outcomes can each alternative give, directly and indirectly, and what is the probability of these outcomes?
3. How does the decision-maker value the outcomes for each alternative?
4. How should a decision between the alternatives be made?

All these questions should be fully answered before a decision can be deemed entirely rational. Since it is generally not feasible to examine all alternatives, or all consequences through time, or define all preferences before a decision is made, the perfectly rational decision is seldom made a reality (March, 1994). Instead, a process to create the best possible result considering the human boundaries of intellect and available information is used, conforming to what is usually called **bounded rationality** (Simon, 1972; March, 1994). This leads to the decision-making settling for good rather than optimal decisions and can be seen as a way of making the decision-making process more efficient (Lejarraga & Pindard-Lejarraga, 2020). It is also worth mentioning that rationality is not a binary but rather a sliding scale from less to more rational.

Another critique of the concept of complete rationality in decision-making can be made from the information-processing capabilities of individuals: one way of describing it is Craik's description of the nature of thought (Craik, 1943):

1. Translation of external processes into internal symbols
2. Reasoning, deducting, or by other means coming up with a different set of symbols that corresponds to the input symbols
3. Retranslation of the new symbol set into new external processes

Given that these translations are not transparent and subject to personal experience, this could be seen as another at least circumstantial evidence that entirely rational decision-making is impossible.

3.3.3 Individual decision-making

When looking at individual decision-making, five aspects are essential to consider:

1. Risk estimation and risk-taking
2. Rule-following
3. Identity
4. Experience
5. Competency traps

Risk estimation is, not surprisingly, the activity of identifying and estimating risks that could affect a decision (March, 1994). March (1994) describes two types of risk estimates; technically and socially valid estimates, where technically valid risk estimates try to describe the objective reality and the socially valid estimate factors in the perceived risks by other actors. Risk-taking describes the willingness to accept risk when evaluating options, and this willingness can vary slightly between individuals and more so within individuals between social situations (March, 1994).

Rule-following, in decision-making, is based on an appropriateness-based logic; the decision-maker recognizes the situation, define their identity in relation to the situation, and tries to find out what is appropriate for a person like the decision-maker (in the type of organization that the decision-maker exists) to do in a situation like the one identified (March, 1994).

Identity affects decision-making if the decision-maker follows an appropriate-based logic for making their decision (March, 1994). Identity ties in with rule-following since professional identities can be described partly by the rules defining the profession and the profession's position within the organization (March, 1994). People have these professional identities (March, 1994) as well as personal identities (Pierrakos, et al., 2009), and the organizations they work in also have identities to some extent (March, 1994). Specifically, for engineers, the ability to make design decisions seems to be an essential part of the professional identity, at least for students (Meyers, et al., 2012). For designers, understanding and managing uncertainty seems to be a central part of the professional identity (Tracey & Hutchinson, 2016). Identity affects decision-making in multiple ways, partly by affecting preferences and partly by people recalling their professional identity (March, 1994). If you are a production engineer, a possible *modus operandi* when facing a possible decision is to ask yourself, ***“what would a production engineer do in this situation?”*** and then let your answer guide your decision-making process.

What type of experience you gain will affect how you make decisions and especially what rules you set up, adapt and follow in a rule-following scenario (March, 1994): exploration and experimentation will result in a variety of experiences, while repetition and exploitation will result in more reliable experiences (due to an increased amount of data and experience). It is important to remember that experience is created from a smaller set of (interpreted) observed events, which is a smaller set of realized events, which in turn is a smaller set of potential events (March, 1994). Therefore, experience is only created from a very small subset of potential outcomes from a decision.

Since rules adapt to their environment, and vice versa, a known phenomenon in rule-based decision-making is the competency trap (March, 1994). Since people learn both what rules to use and how to use a specific rule, from experience, there is a reinforcement loop (Denrell & Le Mens, 2020): if you often use rule A in a particular situation, you become more likely to identify rule A as appropriate and valuable in future situations (March, 1994). This is emphasized if you experience success using A, and therefore start overutilizing A as a solution (Liu, 2006). This gives similar effects to path dependency, as described by Baláz and Williams

(2007), in that previous decisions disproportionately affect future decisions. According to Liu (2006), the demise of the Swedish company Facit (Wikipedia, n.d.) can possibly be seen as an example of a competency trap within a product-producing company. Ullman (2010) describes something adjacent to the cause of the competency trap when writing about procedural knowledge, *“the knowledge of what to do next.”*

3.3.4 Decision-making in teams or groups

When looking at decision-making in teams or groups, four aspects are fundamental to consider:

1. Inconsistency
2. Power
3. Coalitions
4. Logrolling

A significant concern for decision-making in teams is consistency, or rather lack thereof. Even if all actors would be internally consistent and consistent within the team, eliminating conflicts of interest, communication of preferences, and coordination could still hinder efficient and effective decision-making (March, 1994). Nevertheless, there is also a significant risk of interpersonal inconsistencies within a product development team when multiple people with multiple identities and interpretations try to make a collaborative decision (March, 1994).

Power, or the potential of getting your wish fulfilled, will affect the outcome of a team decision-making process (March, 1994). Two significant power models can be found in the literature (March, 1994); force models, where the ability to affect the compromise that is the joint decision is emphasized, and exchange models, where power is described as a trading tool when bringing resources to the decision-making process. What has to be remembered is that power is both positional and behavioral, as well as domain-specific (March, 1994). There is also a depletion effect to power; the more an actor activates and uses their power, the less effective it becomes (March, 1994).

Coalitions can be formed between different actors in collaborative decision-making to maximize all actor's outcomes; it is a form of deal-making between actors with well-defined preferences or identities and seeks to fulfill their preferences to the fullest (March, 1994). Coalitions in the purest sense often require entirely rational actors, but logrolls (where actors are unknowing of or indifferent to other actors' preferences) are perhaps more realistic and can sometimes be used for mediation in conflicts (March, 1994; Qu & Cheung, 2012). Another way of increasing the possibility of successful coalitions is to generate decision ambiguity, making it easier for multiple actors to claim that the decision matches their preferences (March, 1994).

3.3.5 Ambiguity in decision-making

Ambiguity in decision-making is a way of describing a lack of clarity in the reality, causality, or intentionality surrounding a possible decision (March, 1994), either in lack of information or conflicting information (similar to how wicked problems (Buchanan, 1992) are described in design literature). It is a state somewhere

between having precise information and no information at all about a decision to be made, a state that is complex to understand and value as a decision-maker (Ellsberg, 1961). Creating this type of uncertainty might not affect the final decision, but previous research has shown that quantifying uncertainty might impede the speed of decision-making processes (Rydmark, 2020). This is something that might explain why ambiguity is sometimes used as a tactic for creating agreement between partners with different preferences, since the difference in worldview and knowledge that could create disagreement if the situation is fully understood can be ignored and painted as an agreement when adding ambiguity (March, 1994). Moreover, while experience can help with managing ambiguity, it is by no means a perfect solution due to, among other things, the complexity of fully understand causal links when evaluating experience and the noisiness of experience (March, 2017).

3.3.6 Decision flexibility

Decision flexibility is the ability to change a decision in order to make it better suit future changes in environment or preferences (Heimann & Lusk, 1976; Mandelbaum, 1978). This ability can be divided into action flexibility (the ability to change the actions and activities that will be performed) and state flexibility (the ability to manage environment changes within the preset course of actions) (Mandelbaum, 1978). Multiple factors affect these abilities, where the possibility to postpone actions and the willingness to accept change can be mentioned as two examples (Mandelbaum, 1978).

3.3.7 Decision support systems

Decision support systems (DSS) are complex man-machine information systems (Deogun, 1988), that can function as tools for increasing rationality in decision-making. The simplified goal of a DSS is to improve the decision-making process by providing information, either by access to data or analytical models based on larger data sets (Keen, 1980). If well-designed, a DSS should be able to improve all four information-managing problems described by March (1994) as inhibiting rational decision-making:

1. Problems of attention
2. Problems of memory
3. Problems of comprehension
4. Problems of communication

Another point is that DSSs should support the decision-making at all levels of an organization and integrate different levels in the organization (Sprague, 1980). Different design tools have been mentioned as a form of DSSs in academic research (Norell, 1992; Science Direct, 2020), but the main bulk of the work on DSS is still within operations and project management.

3.3.8 Summarizing decision theory in this thesis

Decision theory covers the topic of decision-making and has both descriptive and prescriptive fields. The idea of the entirely rational actor has been disputed and shown to be false due to the vast information needed to make entirely rational

decisions. Instead, concepts like risk-estimation, identity, and competency traps affect decision-making among real-life actors. When looking at decision-making in teams, more complicating factors add, like inconsistency, power, and coalition-building within the team. There are tools designed to help with decision-making, DSS's, and while design tools can be seen as DSS's, most of the work has been done in operations and project management.

4

4 Findings and analysis

In this chapter, the appended studies are summarized, and a generalized description of the findings will then be presented. The following section draws connections between the different studies, and the findings are analyzed. Finally, the findings and analysis are discussed.

4.1 Contribution from studies

The studies appended to this thesis have contributed scientifically to the knowledge of the product life cycle with a heavy focus on the product realization process. When describing the contribution from the studies, the visualization shown in Figure 10 can show where the appended studies have contributed with insights in the product life cycle. For more information of what role the author has had in each study, please see Table 1.

Figure 10. Contributions from studies plotted on the product life cycle (based on a figure previously published in study 5).

All studies contribute to the product realization process, and some of the studies also contribute to the innovation management part of the product life cycle. The main contributions are within the product development phase, both in product planning and design and engineering. There are some significant contributions in production as well, mainly in process planning. This outcome emphasizes the thesis' contribution to the development and realization of new products and how this process is managed within a company. Studies 1-2 have their main contributions in the product development phase, with some added contributions to later

stages of research and development. Studies 3 and 7 are more evenly distributed over product development and production, and they provide the only contributions to goals and strategies within innovation management. Studies 4-6 have their main contributions in product realization, with some additional contributions from study 6 to research and development. The difference between the different studies also shows the breadth of the research: not one of the covered phases is covered by only one study, and all studies have contributions spanning two or more phases.

4.2 Summarizing the studies

The studies are summarized in order depending on their coverage in a product development project timeline; studies investigating conceptual design are presented before studies focusing on production system adaption, for example.

4.2.1 Study 1: On material substitution in automotive BIWs

In study 1, the authors employed a breadth-first versus depth-first approach to engineering design to evaluate the possibility of replacing steel panels with aluminum in an automotive Body-In-White (BIW). The result was that the breadth-first approach proved to halt the case progression, suggesting that this type of approach is unsuitable for these types of projects; the solutions became arbitrary when the information needed became hidden in later stages of the process. The depth-first approach was discussed but disregarded due to the extensive use of resources to fully employ a depth-first project making the approach unsuitable for industrial applications. The complete study can be found in appendix 1.

4.2.2 Study 2: Assumptions of wood

In study 2, multiple case studies were used to examine industrial design engineering students' assumptions and behaviors when working with wood as a design material for products. The main insights were that these students have a distinct behavior when working with wood, a behavior that cannot be described as entirely rational even with the information that they have received. Some can be described by referencing designers' aesthetical preferences, but not all. This points to some shared understanding of the material rather than an entirely rational process. In short, the students act based on how they think the material should behave, rather than exploring and experimenting to see what it can actually do. This shared understanding and these assumptions seem to be a combination of a traditionalistic and boundary-less view of the material, incorporating old rules of thumb and ignoring stigmas. The complete study can be found in appendix 2.

4.2.3 Study 3: Multi material body solutions in the automotive industry

In study 3, an industrial benchmarking was made on different multi-material solutions in the automotive industry and how different companies have implemented material substitution from steel to alternative materials. The study showed multiple solutions existing in the industry, which points to a not yet mature technology or solution. The multidisciplinary challenge of creating a multi-material design was also discussed, with production-related factors integrating into design factors and organizational factors affecting the selection of which materials to introduce and how they should be introduced. To name two examples of production-related factors, the coefficient of thermal expansion difference between materials and split

lines between components were highlighted as challenges to solve in a multi-material product. The complete study can be found in appendix 3.

4.2.4 Study 4: Knocking on wood

In study 4, an interview study was conducted with Swedish wood industry companies to investigate how companies working with sustainable and renewable materials manage material-related challenges in the product realization process. The main insights were that data availability does not seem to be a problem for working with renewable materials, that the organizations trade flexibility for efficiency with an increased size of the production, and that the larger wood industry companies have little in common with the smaller ones with regards to how willing they are to introduce new materials. Some general trends in willingness to work with engineered wood materials (such as plywood, MDF, etc.) were also highlighted. The complete study can be found in appendix 4.

4.2.5 Study 5: Production – as seen from product development

In study 5, a literature review was done on product development literature and its portrayal of production and development. The main finding was that product development literature has a somewhat rigid view of production as separate from product development. According to this, product development delivers information and receives boundaries from production, and there is a historical trend to involve production less in product development activities. In this study, the authors debate if the introduction of DFM and DFA have replaced the efforts to encourage collaboration between product development and production. The complete study can be found in appendix 5.

4.2.6 Study 6: Introducing new materials in the automotive industry

In study 6, a multiple case study was combined with a literature review, observations, and interviews, to understand how new materials could be introduced in the automotive industry. The focus was on how new materials affect the existing products and production system and how products and production systems could be redesigned when new materials are introduced. The main findings were that products and production systems affect each other, that the organizational setup plays a significant role in how new materials can be introduced, and that the introduction of new materials should be considered when module systems are developed in products. As an example of how products and production systems affect each other, the author discussed the effects of joining panels in an automotive BIW. The complete study can be found in appendix 6.

4.2.7 Study 7: Framework for introducing new materials

In study 7, a complementary multiple case study using participation action research was done in the automotive industry. Based on the insights from this study, a preliminary framework for introducing new materials in the automotive industry was designed. The main insights were that organizations optimize themselves around the current materials and technologies used (something that can affect the possibility to introduce new materials), that integrating product and production development is vital for the introduction of new materials, and that the relationship between product and production system needs to be understood and

managed in a material introduction framework. The proposed framework includes work packages from strategic work to continuous measuring and implementing a testing methodology for possible material introduction projects. The complete study can be found in appendix 7.

4.3 Analysis

When considering what affects material-centered decisions, such as material selection, technical parameters like material properties are covered in most basic selection methods. Ashby (2005) covers how to use technical parameters in detail, explaining how product requirements can be translated into material requirements that most commonly are material properties. Even methods centered around material experience and perception (Karana, et al., 2010) or sustainability aspects (Hallstedt & Isaksson, 2017; Mesa, et al., 2018) use material properties at their core. They often focus on more objective properties, but the example with meaning-driven material selection (Karana, et al., 2010) shows that there are subjective and contextual factors involved.

To add to the technological challenges, there are organizational challenges when introducing new materials in the existing production system, as previously shown in studies 3 and 6. However, studies 2 and 4 show that another layer should be added to this; personal aspects. These personal aspects could be, and have previously been, described as designer's preference, but there seems to be more to this. Studies 2 and 4 hints at an understanding of materials not best described as "preference" for a specific material since it does not necessarily correlate with personal opinions of the materials. While some of this can be connected to the problems for rational decision-making explained by March (1994), the focus should perhaps be on **problems of comprehension** rather than **problems of memory**.

To cover the three "layers" of analysis described in the previous paragraph, the analysis has been structured using Berglund et al.'s (2020) description of HTO (Human, Technology, and Organization) as a framework for discussing systems of humans and technology in collaboration within organizations, as shown in Figure 11. While HTO has its origins in human work systems focusing on safety and ergonomics (Berglund, et al., 2020) (both physical and cognitive), it has been chosen since it explains the interactions between the human, the technology, and the organization in which work is made.

In this application, the "technology" moniker is used for a) the physical materials, b) the specific tools and methods used for material selection, and c) the production system. The organization moniker is focused on the company's organization, the team's organization, and the holistic process models for product development work.

Figure 11. HTO, as described by Berglund et al (Berglund, et al., 2020).

4.3.1 Humans

Looking at humans in the product development process, the theory on product development described in 3.1.1 and 3.1.3 shows that decision-making is a central part of product development. When applying the theoretical field of decision theory and analysis described in 3.4, it can be shown that decision-making in product development is not entirely rational. The discussion of the “wicked problem” in product development (Buchanan, 1992) somewhat covers this when describing the problems in product development as lacking a distinct, correct, answer. Suppose you combine the discussion of the wicked problem in design with the design paradox (Ullman, 2010) discussed in 3.1.3. In that case, these complement the analysis that entirely rational decision-making is not possible in product development. However, while not many methods and tools explicitly discuss this, there seems to be an underlying assumption of rationality in many tools since there is no acknowledgment of non-rationality.

Additionally, developers have habits in their design behavior and what type of solution they intuitively prefer and select. This is due to experience and education, which can be seen in studies 2, 4, and 7. Part of this is related to personal experience and knowledge, as Christensen and Ball (2016) discussed. When looking at education, part of engineering and design education is teaching values and ideas, as exemplified in study 5 and touched upon in study 7. On the other hand, this cultural aspect is not discussed in the studies included in this thesis. The cultural aspect, sometimes called professional identity, has been covered in engineering and design education literature, as discussed in section 3.3.3.

In specifically study 2, the non-objective parts of material selection and management are highlighted. The students in the study are not making material choices solely based on objective material qualities but rather their perception of material characteristics and behavior. This appears to confirm the existence of some sort of mental models of materials, similar to the translated models described by Craik (1943). These mental models can be closer or more distant to the objective description of the material and will be built upon and modified throughout a developer's education and career. The presumed existence of mental models of materials will affect decisions, assuming that developers work with bounded rationality. This existence of mental models also means that added data might not be enough to sway a developer to change a decision (i.e., choosing a more sustainable material in a product), since the availability of data itself is not directly related to the decision-making mechanisms (the mental models). Instead, to encourage sustainable material choices, multiple aspects must be addressed to manipulate or modify the mental models of materials for developers or to modify the design space via external means.

Combining both developer habits and mental models of materials will mean that the perceived design space will differ from the theoretically complete design space. Assuming this, the same goes for the possible routes through this space to find a solution. It is complicated, perhaps even impossible at this stage, to define the exact differences between the perceived and theoretically complete design spaces, but their mere existence will affect how a particular solution can be encouraged by external means. There is a possibility that more sustainable solutions will be missed when exploring the design space since either that part of the design space or the route through the design space to get there is not perceived as existent to the developer.

One thing that is shown in study 2, and peripherally discussed in studies 6 and 7, is that developers tend to revert to known-to-them materials when allowed to, as well as when exploring materials to combine with new materials. This could, perhaps, be down to a risk-managing approach where the developer wants to keep the number of unknown parameters at a manageable level; perhaps an internalized MAYA-stage (MAYA: Most Advanced, Yet Acceptable, from Loewy (1951)) for the developer. To understand this behavior, the goal of the product development process should be discussed. Is the product development process a learning process, an opportunity-maximizing process, or a risk-minimizing process? While industrial designers have a view that could be described as opportunity-maximizing, engineers might tend more towards risk-minimizing, as Brunsson (1980) alluded to

when describing decision-making in engineering. If one looks at material selection from a risk-minimizing standpoint, reducing the number of unknown parameters and avoiding a combination of unknowns (for example, multiple new materials in one component) is a very reasonable approach to solving the problem. Suppose we are to use the MAYA concept internally on the developers working on the products. In that case, this could also be understood as a way to keep the product within the acceptable range as a developer. In this case, the “acceptable” concept in MAYA would not be pointing to the limit where the product cannot be understood as a specific product, but the limit where there are too many uncertainties for the developers to manage. The question is not whether the developer understands the product but rather the unspoken question, “*can we get this done?*”

The competency trap, described in 3.3.3, will also affect individual preferences for materials. Suppose an engineer has extensive experience with material A. In that case, they are more inclined to preference material A even when it is not the most suitable material to solve the problems expressed in the project brief, simply because they have experience using A and therefore know what problems might arise when using it. This could explain some of the effects seen in studies 2, 4, and 7 to some extent, by making the developers prefer solutions they are familiar with to a non-rational extent over solutions that could be theoretically or technically better for the proposed challenge or problem.

The effects of the competency trap emphasize the need for continuous learning to reduce the risk for new competency traps and MAYA-inspired risk management in material selection. If developers continuously learn how to manage new materials, the risk for MAYA-inspired risk management behaviors might become reduced, lowering the risk for competency traps.

4.3.2 Technology

While physical material properties are central to the material selection process, properties relating to the perception and experience of the product are not as commonly covered. In Ashby (2005), this can be derived from some of the product requirements, but the experiences that the author is referencing here are often hard to quantify. Some efforts are made in this field, with different types of soft metrology (Eriksson, et al., 2018), but this is time-consuming and not consistently implemented. Researchers with a design focus have introduced material perception and experience in separate material selection models (Karana, et al., 2010; Wastiels, et al., 2012). However, the combination of the hard, engineering-related, or easily quantifiable properties and the soft, design-related, or hard-to-quantify properties are still conceptually complicated since they are differently suited to different approaches.

In a situation with non-comparable data, traditional methods also have significant shortcomings. For example, when data for different material options describe substantially different properties or include a high level of uncertainty, the traditional material selection methods struggle with aiding the developer. When being forced to rely on non-comparable data or lacking some specific data point, a fully viable material might be excluded early in the process due to the information gap. When looking at data with differing levels of certainty, methods like Ashby (2005) tend to

favor the material with more clearly defined data. In both these cases, new materials will be at a disadvantage in the product development process. This effect could have been a factor for the developers in study 2 reverting to “known” materials since these materials are usually very data-dense. Using material samples to test and gather new data, similar to the exploration phase in Material Driven Design (Karana, et al., 2015), is possible but will slow the project down. This possible bottleneck will also favor established, well-known materials since project time and budget are correlated and parts of measurable characteristics of project success.

Introducing a new material will also put some form of strain on the production system. Since materials have different properties, as discussed in 3.1.5, the needed solution space or competency space needs to increase for the production system. As discussed in 3.2.1, flexibility provides some tools for analyzing the differences between the current state and the desired state. In studies 1, 5, and 6, the material changes also drive design changes; fasteners, geometries, and joining methods (among others) can be subject to change after a material change. Suppose we assume that multiple products are made in the same production system, and that not all existing products will be redesigned after a new material is introduced somewhere in the product portfolio. In that case, some flexibility in the production system is needed to manage this without a system redesign. This means that material flexibility should be included when strategic decisions regarding production flexibility are made to prepare for future material introductions.

Studies 3 and 4 also point towards a multidimensional challenge when managing multiple materials, and studies 4 and 7 points towards a conflict between material flexibility and efficiency; the more streamlined a production process is, the less-suited it is to manage the introduction of a new material. In less efficient processes, introducing a new material is much less worrisome since slower tact times can be managed within the existing production framework without too significant consequences.

4.3.3 Organization

When analyzing product development processes, study 1 can be used as a critique of the linear process described in, for example, Ulrich & Eppinger (2008); study 1 shows the problem with using both linear breadth-first models (decisions becoming arbitrary due to a lack of much-needed information) and depth-first models (extensive use of resources). The linear model seems unsuitable for projects with moderate-to-high levels of uncertainty and many coupled decisions, essentially ruling out more complex designs and projects. This is also discussed in study 6, suggesting the need for more flexible and adaptive process models for product development. One way could be to do away with the entire problem-based development process and instead look to processes like MDD (Karana, et al., 2015). This is interesting, but it would necessitate a revision of the entire company and its mission and vision, which might not be suitable. While the industry segment and products usually define a company, an MDD-based company would probably define themselves by the development capabilities and materials used in their products. Instead, there is a need for a new problem-based development process to manage issues regarding how new materials can be introduced and fully valued.

In study 6, the author emphasized the organizational aspects of introducing a new material. This was also exemplified in the framework developed in study 7. In study 7, suggestions of knowledge and information sharing pathways were made to reduce organizational rigidity, which has been identified as a risk factor when introducing new materials. But what is organizational rigidity?

Organizational rigidity is an effect of efficiency gains. Organizations optimize themselves for the materials they are manufacturing in, reducing the flexibility to introduce new materials. This was shown in studies 4 and 7, with it being one of the main conclusions from study 7, given that this study looked at a larger company with a more automated production system. The tendency to optimize the organization towards rigidity is especially true in mass production. The conflict between efficiency and flexibility gets increasingly volatile with larger production volumes and revenues and can affect an organization's ability to adapt to new materials. Some of this can be resolved by collaborating with suppliers (something mentioned in the interviews in study 4), but not all of it. Widening the concept of flexibility could aid in creating a possibility for more risky material choices and give a technological system in development and manufacturing that can manage a broader range of geometries and material properties. Introducing this should also help create decision flexibility, as described by Mandelbaum (1978). A more flexible production system can help create state flexibility, and the more flexible organization can create action flexibility, both factors needed to achieve true decision flexibility.

Going back to the theory described on decision-making in groups or teams, as described in 3.3.4, concepts like preference inconsistency and power will affect how project teams behave regarding material selection. When attempting to screen and rank options, there are also opportunities for logrolling between actors, in order to favor a specific material or a specific set of parameters that will favor a material. As described in 3.3.3, competency traps will also affect teams, especially when combined with formal and informal power structures. Suppose a senior engineer or designer has experience with material B. In that case, this could weigh more than a junior engineer suggesting that material C might be a better fit for the product.

4.3.4 Humans and technology

How humans experience materials and products differ between individuals, as described by Fenko et al. (2010), partly due to the mixing of literal and figurative meaning in interpreting a product's properties. This implies that identity affects material experience and that this will affect, for example, preference in material selection. If non-quantifiable aspects are taken into account, the decision-makers' experience and identity will affect how they perceive certain qualities in a material. This will also be seen in the ranking of requirements importance which will affect the outcome from a process like Ashby's (2005) for material selection.

This diversification in experience and preference, combined with material properties and production flexibility, can explain some phenomena shown in studies 2 and 4. When companies try to center their work on a set number of materials to

make the production more efficient, this will affect both the need for production flexibility (and thus the ability to adapt to new demands) and the skillset within the employee base. This can be at least partly resolved by collaborating with suppliers, as mentioned in study 4. However, if this is not emphasized, the effects shown in study 2 can have a more significant effect, with developers implementing one new material and then shying away from using other new materials even if they would provide an advantage in the product.

4.3.5 Humans and organization

The question of power, as discussed in 3.3.4, becomes a challenge in decision-making. What types of power will generate an impact on the decision, and how does this intersect with, for example, the identities of the decision-makers? The group will collectively develop a set of preferences that will be affected by the individual preferences and the group dynamic. This dynamic will come from the organizational structure (formal power) and factors like experience and identity (informal power). The group dynamics might affect which identity a person prioritizes when reflecting upon preferences. These fluctuating or changing identities, with power changing between different identities, will affect the outcome of the group's decision-making process.

One of the findings from study 4 can also be discussed there; the company's organizational identity, focusing on how it describes its output. In study 4, three types of company descriptions were identified, and these could be traced back to organizational identity. This organizational identity will also affect power structures since some tasks, activities, and knowledge align with the organizational identity more than others. These tasks, activities, and knowledge will therefore be emphasized in both formal and informal power structures.

The effects of developers' mental models of materials will also affect when working in teams since all developers might not have the same view of the possible design space. What one developer sees as a distinct possible solution might seem entirely impossible for another, without the need for any difference in their understanding of what should be done; they can agree fully with each other on the specification but still differ in opinion on the possibility. This means that one developer can see a more sustainable solution as possible but not have the team acknowledge the idea. The inverse can also be possible; developers believe in an impossible solution because their mental model of a material or a production process might be too optimistic, as in allowing too much. Depending on the developers' power, official or unofficial, this can affect the outcome of the product development process.

4.3.6 Technology and organization

The intersection of technology and organization will be affected by intrapersonal factors (the intersection between product development process and product development tools and methods) and by physical factors (the intersection between materials, production systems, and the organization of work). The concept of flexibility on different levels (as discussed in 3.2.1 and 3.3.5) becomes essential here since the prioritization of types of flexibility will affect the organization as well (assuming that the gains in flexibility will come at some cost); an organization focusing on be-

ing flexible towards workload will have a different work process and structure than one focusing on differences in input. In the first case, the ability to move people around and have “everyone able to do everything” might be prioritized, while experience might be more prioritized in the latter.

The materials used will also affect the organization since materials have different properties and require different solutions. The use of fiber-reinforced polymer composites like CFRP (carbon fiber reinforced polymer) can be used as an example. Since composite materials like CFRP are created (or rather: put into their finalized state) in the same process as the manufacturing of the component, large-scale use of manually laminated CFRP components generates a need for integrated product development and production development processes. More so than would be the case with many other materials. The production system affects the material properties to such an extent that production preparation and structural engineering have a significant overlap when working with manually laminated CFRP. This means that the material affects the product and production development process since it demands an integrated workflow. Similar effects can be seen when working with wood veneer laminates. However, the organizational structure also affects which materials are used and how easy it is to introduce new materials, as was discussed in study 7. This relationship between organizational structures and materials is somewhat similar to the relationship between the production system and the product that was discussed in study 6; there are multiple interconnected systems that are developed separately, but where the interconnectivity should be addressed in order to reduce the risk of failures.

4.3.7 Humans, technology, and organization

In the intersection between all three factors, combinations of previously mentioned challenges coincide. It could, for example, be challenges of power, human rationality, and flexibility, that interact with each other to create more complex networks of unknown parameters within the decision-making process.

For example, let us look at a case where developers with preferences design products in new materials within an organization set up for working with perhaps different materials than what is now being used. In this case, we get the developer’s mental models of how a particular material “should” behave, and how design and engineering “should” be done, within an organization with specific communication pathways and processes to ensure that developing in another material is being done as efficiently as possible. This product should be made in a production system that might be flexible, but it is ultimately designed for other materials. Even if rational decision-making was possible, the number of unknowns in this system are numerous, and thus the risk for failure and inefficient products or development processes increase.

4.3.8 Summarizing the analysis

The introduction of new materials is a multidimensional challenge, following the core description of sociotechnical systems as described by Clegg (2000). The decision-making preceding the introduction must address technological needs, available knowledge and data, developer behaviors and habits, organizational behavior and habits, material and supplier availability, and production system capability and flexibility, among other factors. This multidimensionality, and multiobjectivity, makes for a very complex problem with many unclear relationships between decisions and unclear causal effects.

Material selection and material management in the development of new products can be analyzed from a Human-Technology-Organization perspective, in order to untangle some of the complexities of the situation. This also shows that tools and methods designed to help with material selection should take all these perspectives into account. Figure 12 shows aspects that affect material selection in a product development project, arranged according to the Human-Technology-Organization perspective.

Material selection and management is not a rational process. At the very least, it is constrained by human bounded rationality. It is also affected by the dimensions mentioned in the previous paragraph, and the impossibility of capturing and processing all the data makes entirely rational decisions an impossibility. Treating it as a rational process, or assuming that rational processes and methods can be implemented, would impose a risk for the prescribed process to distance itself from the actual process; there will be one process on paper and one in reality. This will have adverse effects since traceability and accountability will suffer from such a distancing, as well as the possibility to develop design methods and tools further.

Finally, it can be said that material introduction/diversification and manufacturing flexibility are dependent aspects in the product realization process. This means that flexibility strategy development should include material strategies and vice versa. It further emphasizes the need for an integrated process between product development and production development.

Figure 12. Aspects that can affect material selection, following the Human-Technology-Organization perspective.

4.4 Discussion

In this subchapter, the author will discuss the different studies' findings, their applicability, and the analysis and its validity. Specific discussions regarding the research methods can be found in chapter 2.

4.4.1 Discussion of the findings

The findings presented in this thesis stem from a profoundly interdisciplinary challenge. While spanning from abstract and theoretical in philosophy to applied in production technology, it also spans different views on knowledge, from positivism emphasizing objective truths and empirical evidence, to relativism or antipositivism emphasizing meaning and how the researcher is affected by their surrounding

environment. This means that the interdisciplinarity of the topics covered is multilayered and complex; fundamental truths and assumptions in one field might not be considered such in others. In the writing of this thesis, this has proven troublesome at times since different fields have had different definitions of the same terminology, and some basic concepts from different fields have been unacknowledged in others.

The findings from the research presented in this thesis have been iterative; each study has provided some puzzle pieces to help get a complete understanding of the topic. This has affected both the research method and the findings since the added knowledge has been used to deepen and widen the scope of the following study. The iterative approach has reduced the risk of having more significant gaps in the empirical data. However, it has also lessened the depth and possibility to validate studies (since the focus has been on compiling complementing data rather than replicating studies to validate the results).

Some of the case studies have used student projects as the unit of analysis, creating a level of abstraction from industrial projects. This has been deemed acceptable in this type of research, based on four major contributing factors; the presence of industrial projects, the setup of the student projects, the validity of student projects in product realization, and the ability to gather specific amounts of data.

The presence of industrial projects in the research means there is still a connection to industrial work in the thesis; the work is not entirely dependent on outcomes from student projects. This also means that the student projects can be compared to industrial projects, and more significant deviations can be investigated early in the study process.

The student projects' setup was done to mimic industrial work to a certain extent; the student teams have had extensive autonomy in their work and have collaborated with external partners in several of the projects studied. This, along with the possibility of repeating projects with altered input variables and participants with similar experience and skill levels, has allowed the author to understand the effects of certain parts of the project setup and the project brief.

The validity of student projects in product realization has been evaluated in collaboration with the industry, and given valid input parameters, the students seem to produce results close to what developers in the industry would do with the same brief. The author has assumed that if the project briefs have been realistic in an industrial application and the results have been similar to applicable real-world solutions, the process of developing these results should be close to the actual process.

The ability to gather data without IP complications and internal politics at companies has made for a much richer dataset to analyze. This richness in data has not been possible working with only industrial projects and has been deemed contributing more than the abstraction from industrial work has hampered the dataset.

The use of a compilation thesis can, as has been tangentially discussed in 2.3.1, be viewed as a way to help the author validate the findings throughout the research: the continuous publishing through peer-reviewed conferences and journals have created checkpoints for the findings, where they have been discussed and evaluated as separate entities at various points throughout the process. This, on the other hand, means that the author has had to evaluate the validity of compiling findings from different projects, and some findings from different studies have not been included in the thesis due to either lack of applicability, further development of research approach, or lack of relevance in this thesis.

Still, the findings from the case studies are explorative; they cannot be used to define, for example, the extent to which a mental model affects a developer's decision-making or how much organizational rigidity is "too much" to reduce the possibility of sustainable material choices, they can only be used to raise questions at the moment. While these questions are essential and have a basis in real projects from industry and academy, an interesting next step would be to try and define and measure the effects or even establish some causality or relationship between factors and effects.

While the results are explorative, and the findings depend on the research methods used, the author would argue that the findings contribute to the public body of knowledge regarding product realization. As shown in the introductory chapter, there is a gap in knowledge that the author has attempted to fill in with the findings from their studies. This approach to adding to the public body of knowledge has carried through into the analysis of the findings.

4.4.2 Discussion of the analysis

The analysis has been done in multiple iterations; every study has added understanding and new, iterated research approaches and questions for the subsequent study. While no holistic theory has been formulated during the research, as discussed in 2.7, knowledge gained from previous studies has informed the design of future studies. While this could result in some path dependency, given that the researcher becomes restricted regarding how much a new project or study can deviate from the previous ones, it was deemed the most appropriate approach for this type of explorative research. The variation in methodology, and the use of both **Research through design**, **Research into design**, and **Research for design**, has been used to mitigate path-dependency effects in the research, adding new viewpoints throughout the research.

During the analysis phase of the work, the author has added theory from decision theory to explain some effects in developer decision-making that did not seem to be possible to explain with more conventional means. In a perfect research setup, this would have been included earlier and in the study setup. However, it has not been deemed a severe weakness due to the richness of the data gathered in the studies. While some studies might have been more suitably designed if decision theory had been included earlier in the overall research process, the broad data gathering mitigated the worst effects of not including decision theory in the study design process.

Applying the HTO framework from Berglund et al. (2020) is a novel use for this type of framework. HTO itself has a background in workplace safety work (Berglund, et al., 2020), and the application of design work is not itself obvious. Berglund et al. (2020) use the design of products as an example of an application, but use this application to understand the use case of the finished product rather than to understand the process of designing the product itself. Still, the author found that the framework and terminology could be used to aid understanding of the design process itself when talking about the development of physical products and investigating tangible aspects of the product (the materials).

Initially, the objective of this research was to present a new framework or methodology for product realization, focusing on material selection and related aspects. This shifted throughout the project towards further understanding the inner workings of the product realization process and how developers act within it. While this decision has made the research deliverables less tangible, it was evaluated as the best choice since it enabled a more elaborate analysis of the data and the aspects that can affect decision-making in product realization. This more detailed analysis can be used later, either by the author or other researchers, as a basis for the development of a new framework or methodology for product realization.

5

5 Exemplifying material decisions

In order to visualize the findings in this thesis, the author has chosen to write a fictional case of material selection within a product development project.

This example has been created using design fiction to explain and visualize design processes and decisions. The case is in some way idealized, not from a “perfect decision-process” standpoint but from a visualizing standpoint: the author has attempted to cover as many aspects of material selection within product development as possible.

This chapter aims to provide a (fictionalized) detailed example of the intricacies of a material selection process, to be able to use it as a separate document in discussions regarding material selection processes, and to visualize the processes involved for tool and method development purposes.

5.1 Design fiction

Design fiction is a research method aimed at unfolding or unearthing ideas and commentary that cannot be done via conventional means. Lindley (2018) describes design fiction as world-building and as a way of making theory and generating new knowledge or communicating ideas. These can be used as suggestions for future worlds or to generate a discussion about specific technology or processes (Lee-Smith, 2019).

Some analogies to design fiction can be found in personas, used in design to create stereotypical users from user data and humanize the design process (Dam & Siang, 2021) in milieus where participatory design approaches might not be possible (Matthews, et al., 2012). Some research has shown that designers use personas to communicate but not to perform design (Matthews, et al., 2012), since personas can be perceived as abstract and misleading for design work. Personas have been used for multiple purposes, such as understanding the goals of the user, behavioral patterns, and creating involvement (Dam & Siang, 2021). Design fiction could also be argued to be a variant of speculative fiction (Oziewicz, 2017) or science fiction. Science fiction, in turn, has been used both as inspiration and consumer priming for new technology previously (Budd, 2016). In this thesis, design fiction has been used as a tool to bring a holistic view of the material selection process and management of material aspects in the product development process. A fictional case has been set up to visualize the different aspects that have been covered in the research, both in the studies and in the reviewed literature. The data collected in

the studies have been done using traditional means. However, the visualization and communication have incorporated design fiction as a tool to fuse details from multiple cases and respondents. The use of design fiction has also made it possible to discuss personal aspects in design work while still vouching for anonymity for study respondents.

The focus of the design fiction work in this thesis has been on visualizing the probable and plausible in a product development process, rather than the possible or preferable; the combination of effects from different cases has been done based on whether the combined effects are reasonable to imagine together, rather than if they can possibly occur together. This type of writing has been inspired by the *A Day in the Shop* segments of Bengtsson (2008), where the work in a retail shop was exemplified and detailed similarly. The design fiction case has not been used to show what a preferred state is, since this an altogether another question that requires much further research.

In future technology and tool development, the design fiction case can be used as a version of a persona; rather than using a real case, tool developers can use the fictional case to get a preliminary indicator if their tool would solve problems the case visualized or if the process would look the same with or without the tool envisioned. This also means that one of the contributions of this thesis is to evaluate whether design fiction can be a valuable tool for product development research by using it as a visualization technique for intricate findings regarding behavior in the design process.

5.1.1 A critical review of design fiction as a research method

As Lindley (2018) discussed, the concept of design fiction is still in a pre-paradigm or early-paradigm state. This means that there is no straightforward best practice for how to use these methods while keeping scientific validity. This lack of a best practice can undoubtedly be managed but necessitates caution when the method is used. A risk when working with design fiction is to create fiction with little or no connection to reality; instead of using fiction to visualize or explore real issues, it can be used to fabricate issues or aspects of life if used incautiously. Even when the researcher uses design fiction as a communication method, readers can perceive the fictional parts as real and arrive at erroneous conclusions. Lindley (2018) uses the famous radio broadcast of H.G Wells' War of Worlds, made by Orson Welles, as an analogous example of the possible risk of the recipient mistaking fiction for reality. Due to this, the researcher must be explicit about where fiction is injected and how design fiction is used.

The risk of using a design fiction case as a persona for tool development lies in its applicability: does the fictional case reliably describe probable and plausible courses of events and decisions? If not, the tools developed using the fictional case will risk being of little to no value.

In this thesis, design fiction has not been on using design fiction to investigate but rather to visualize. This should decrease the risks of using design fiction creating false narratives or false issues; the issues described in the fictional case are derived from findings in the other work and not speculative at its nature. In order to min-

imize the risk of confusing fiction with reality, a separate chapter is used for the fictional case. This has been done to not mix actual data from other studies with the fictional case. It is also presented after the analysis as a visualization of the challenges identified in the analysis chapter, in order to emphasize the difference between the actual data, the analysis of the actual data, and the fictional case.

The use of design fiction as a tool for visualization was a late addition to the work to explain further and make the analysis and conclusions more relatable for a reader. Design fiction could be used for many different purposes, some much more experimental than the one used in this thesis, but the method is still novel in its implementation. As discussed earlier, there are challenges with using methods like design fiction and keeping reliability in results, which is why both the late addition and the limited scope can be seen as not negatively affecting the outcome.

5.2 The company and project team

In this fictional world, Söndermarken KB makes air humidifiers for a smaller, more design-oriented customer segment. The company has its headquarters in Hudiksvall, Sweden, alongside its design and engineering office and production. All in all, there are 130 people employed at the headquarters; 80 are working with production and logistics, 10 people work with production and purchasing, 15 are working with engineering and design, 5 people work with sustainability and infrastructure, 10 are working with sales and marketing, and 10 people have administrative tasks.

From these 130, one production machine operator (Adnan), one production engineer and planner (Benny), two design engineers (Cecilia and Daniel), and one sales director (Eva) are set out to do Project Alpha. Project Alpha is the new line of air humidifiers that Söndermarken KB will have in their product portfolio, that will focus on sustainable living for younger customers with lower incomes and thus less money to spend.

Adnan (Figure 13) wants to make sure that the new product is easily manufactured and assembled; the company has had some older product lines in production that were unnecessarily finicky and complicated to assemble and required the use of some older, not that safe, machinery. Adnan is a 40-year-old man that has grown up in Hudiksvall and lived there his whole life. He has worked at Söndermarken for the last 20 years. He is also very involved in civil society, especially sports.

Figure 13. Adnan. Picture from <https://thispersondoesnotexist.com>

Benny (Figure 14) wants to reduce the cost for the product and reuse as many parts as possible; the old processes are optimized, and it will take time to tune in new parts or processes to make them as efficient as possible. Benny is a 50-year-old man that has grown up in a small city two hours from Hudiksvall and studied engineering in Stockholm. He has worked at Söndermarken for the last 5 years; before, he worked in Stockholm but moved with his wife when she wanted to be closer to the family as their children had moved out.

Figure 14. Benny. Picture from <https://thispersondoesnotexist.com>

Cecilia (Figure 15) and **Daniel** (Figure 16) have looked into the design and technology trends and want to include some new features into the product to ensure that it is relevant for as long as possible. Cecilia is a 25-year-old woman that has grown up in Hudiksvall and went to Luleå for her studies in engineering before moving back home. She has worked at Söndermarken for 2 years.

Figure 15. Cecilia. Picture from <https://thispersondoesnotexist.com>

Daniel (Figure 16) is a 32-year-old man who grew up and studied in Gothenburg before moving to Hudiksvall with his husband, who got offered a job as a doctor at the local hospital. Daniel has worked at Söndermarken for 5 years, having worked in the automotive sector before.

Figure 16. Daniel. Picture from <https://thispersondoesnotexist.com>

Eva (Figure 17) has been looking at the current market offerings and talked to some possible new vendors. From what she can see, renewable materials are on the uprise, but it is not clear what the most popular solution would be. Many companies are still trying things out. Eva is a 40-year-old woman who grew up in a small city in Småland and has lived in Hudiksvall for 20 years. She moved there to live with her at-then boyfriend and has worked in sales for the last 15 years, starting as a reseller and moving into technical sales and sales management in later years. She started at Söndermarken 10 years ago and has been a sales director for 4 years.

Figure 17. Eva. Picture from <https://thispersondoesnotexist.com>

Additionally, Design For Environment engineer Sandra has looked into what new material restrictions might be on the horizon and has informed the team that the “Right to Repair” might become more important in future years, something that should be considered when developing the new line.

Project Alpha will use approximately half of the production staff if the project is successful. When we come into the project, the project team is contemplating using either recycled PET, aluminum, or birch veneer-based laminate for a part of the casing of the humidifier. Söndermarken can manufacture components in PET on their own, has a supplier in Estonia for cast and pressed aluminum components, and has suppliers close by (in Hudiksvall) that can make the veneer-based laminate. Long-term, there are discussions of installing machinery to make aluminum components in-house, but the risk is deemed too high to invest right now. In the early stages, solid wood and polycarbonate materials were considered, but they did not match the product’s price range or customer demands.

The whole project team will be involved in the decision since they have been hand-picked for the project due to their different experiences. Söndermarken works strategically to reduce non-value-adding work and thus has implemented a strategy to include representatives from all affected areas early in the project. The CEO likes to say that *“everyone should have a seat at the table.”*

5.2.1 Söndermarken’s product development

Söndermarken KB uses an adapted version of Ulrich and Eppinger’s model for product development (Ulrich & Eppinger, 2008), with four gate meetings added; strategy and requirements review, concept review, engineering design review, and pre-production review. Since the engineering and development part of the company is comparatively small, parts of Andreasen and Hein’s ideas of integrated product development (Andreasen & Hein, 1986) are organically integrated into the work process.

For material selection, the company uses an Ashby-inspired material selection process to translate product requirements into material requirements, screening, ranking, and searching for supporting information. The company has a rudimentary R&D department and workshop, with some possibilities of actually testing materials resulting in the developers often contacting suppliers to get detailed material data instead of creating their own. In the workshop, though, there are extensive possibilities to build and test prototypes.

This material selection in this case is a multiple-choice decision between different possible materials for a component in a consumer product. The concrete decision situation can be formulated as follows: ***“Which material should be used for the fascia panel of this air humidifier?”*** There is a discrete set of clearly different options, all different and, in theory, comparable materials (since the decision not to select a material is not considered; it would either mean a delay of the project or a suspension of the project itself). These materials are recycled PET, aluminum, and birch veneer-based laminate. The relevant decision-makers are clearly outlined (and included in the formal decision) in the project team. There is also some clear, perhaps implicit, preference to make the best possible decision for the company, often described as optimizing for company profit.

In reality, the preferences are implicit and divided. While all relevant decision-makers (the previously mentioned developers) would probably agree to something similar to ***“we all want to make the decision that is the best for the company,”*** and explain this best for the company as defined by profitability, there would be an apparent disagreement on what would be the best decision for the company. There are multiple different preferences of what is most important for a good decision; Adnan might prioritize ease of assembly, while Daniel might have his preferences set to prioritize the integration of future technology, and Eva will have a preference for selecting a renewable material. Suppose the team is considering the input from Sandra to a more considerable extent. In that case, they might prefer a material suitable for multiple disassembly and assembly sessions to manage the right to repair.

5.3 The decision-making process

Here, three different scenarios will be presented. They represent three different sets of factors affecting decision-making that can be seen as non-rational.

5.3.1 Scenario 1: Different mental models of materials and processes

When the team sits down after lunch, they turn to the next point on the agenda: Project Alpha. Eva brings up the slide with the product requirements, and they start to discuss their options.

Eva: *“So there are three options left: aluminum, PET, and veneer. What do you think of the options?”*

Benny: *“Do we really think that that veneer would work? I just think it will be too expensive.”*

Adnan: *"Why expensive?"*

Benny: *"It just seems so complicated to get into our production; we have to restructure a lot of our work."*

Cecilia: *"Okay ... Is there any way to make it easier?"*

Benny thinks for himself. He sees a wood workshop. And splinters. So many splinters. What happens when the veneer parts won't fit? Wood moves and expands; it will be a mess. Better to work with something more predictable.

Benny: *"No, I don't think so. I think aluminum would be a lot cheaper to manage in production."*

Daniel: *"Okay, but wouldn't that need a lot more milling capability?"*

Eva: *"I think we can actually get all the holes and geometries we need to be stamped into the part at our supplier; they have promised similar things before."*

Daniel: *"Okay, that's good."*

When the team goes to get coffee, Daniel chats with Cecilia about using veneer.

Daniel: *"Too bad the wood option is too expensive; it would have been nice not to have to use adhesives."*

Cecilia: *"Yeah, the front fascia concept you showed was really cool. And I did the calculations; it would be almost as stable as the PET designs. But I guess aluminum works as well?"*

Daniel: *"If our supplier does its job, absolutely. Did you see the first deliveries of the Sigma project? Everything was warped."*

Cecilia: *"Oh, that's not good ..."*

Meanwhile, Adnan and Eva discuss their supplier of aluminum components.

Adnan: *"Have you talked to Luuk about this component yet?"*

Eva: *"No, but we have talked about similar parts before, so there shouldn't be any large differences. And Sigma worked out fine, right?"*

Adnan: *"There were some teething problems, don't you remember?"*

Eva: *"Of course, but there are always problems, but it ended up fine, right?"*

Adnan: *"I guess so."*

Cecilia still has some questions for Daniel.

Cecilia: *"So, how much do you think we need to change?"*

Daniel: *"A lot, we have to start from scratch, really. Sigma was probably as far as we could take that design, and it was terrible. You've seen the inside, right?"*

Cecilia: *"Oh yeah, no offense, but I've seen better ..."*

Daniel: *"None taken; it is bad! Hopefully we can do a lot more with the front fascia this time and not be limited by our old framework."*

They all get back to the meeting room.

Eva: "So, are there any questions still before selecting aluminum?"

Daniel: "How can we assemble everything?"

Adnan: "We could make do with the current system, but if we can use fewer bolts, it would be great."

Cecilia: "So maybe some adhesive?"

Daniel: "Can we use anything we've already got?"

Benny: "The Ausch stuff should work, I think?"

Adnan: "What's the cure time on that?"

Benny: "10 minutes before any load, 30 minutes before fully cured."

Adnan: [Sighs] I think we can make it work ...

Eva: "So we settle for aluminum?"

The team agrees to decide on aluminum for the fascia panel.

In this scenario, Benny lets his mental models of wood and wood manufacturing affect his preferences in the decision-making process, and his somewhat traditionalist model informs him that the material will not work in the production system. His view of both materials and processes differs from Daniel's and Cecilia's, who emphasize other aspects of the birch veneer in their mental models.

5.3.2 Scenario 2: Different professional identities and experience

The team pours into the meeting room, one by one. It had snowed during the night, so Daniel and Eva, who could walk to work, showed up first. Benny was the last one in; he lives out in the woods and had to clear the road all the way down to the main road before he could drive to work. Adnan initiates the meeting.

Adnan: "So about Alpha, what should we do in terms of materials? Did you have some candidates, Daniel?"

Daniel: "Yes, we're down to aluminum, PET, and veneer. All should work, but they have their pros and cons."

Adnan: "Great, any thoughts on the suggestions?"

Benny: "How could we make veneer work?"

Eva: "I guess we'll work with Sundin's if nothing else shows up."

Benny: "And aluminum would be Luuk again, I guess?"

Eva: "Probably, if we cannot find anyone else."

Cecilia: "Have you worked with aluminum before?"

Eva: "Yes, we did Sigma in aluminum. It worked out okay, didn't it?"

Adnan and Benny, in sync: "Define okay ..."

Eva: "Ah, yes, there were some initial issues, right?"

Benny: "That's not an exaggeration ..."

Eva: "So ... should we look for someone else?"

Adnan: "That could be an idea; we had to scrap so much in the beginning."

Eva: "I'll keep that in mind. But do we want aluminum? I'm not sure that is the easiest thing to sell right now."

Adnan: "We could work with it in production, but what do you say, Cecilia and Daniel?"

Cecilia thinks to herself, what would be the best solution? She thinks back to her bachelor project, what did the supervisor say again and again: think like an engineer. The aluminum is nice and easy to calculate, and the veneer solution is sustainable. But natural materials are not that nice to work with, and aluminum can get expensive.

Cecilia: “Adnan, how much easier would it be for you just to snap the electronics to the front fascia and then snap the fascia to the mainframe?”

Adnan: “It would solve so many problems! But can we do that?”

Cecilia: “I think so if we use PET. Or what would you think, Daniel?”

Daniel: “Yeah, we can make that work. The tools will be expensive, but assembly should be a lot easier.”

Adnan: “If we make it quicker to assemble it, it will be worth it.”

Cecilia: “Great! I have done snap joints a few times; what about you, Daniel?”

Daniel: “I made a lot of those at my old work; I should still have the design guidelines somewhere at my desk ...”

The team decides to select PET for the fascia panel.

In this scenario, Cecilia draws from her professional identity as a mechanical engineer to determine what an engineer would do in this situation. She also encourages Daniel to draw from his earlier experience from previous jobs when the challenge of snap joints is brought up. In the first exchange, you can also see the different experiences of Eva on the one hand and Adnan and Benny on the other, when they discuss experiences from earlier projects. This difference of experiences could stem from different professional identities, where Eva as a sales director, emphasizes other aspects than the more production-focused Adnan and Benny.

5.3.3 Scenario 3: Different personal identities and world-views

While Adnan is getting a cup of coffee, the others are sitting down in the meeting room. They are chatting about their weekends and what vacation plans they have. Adnan sits down, and the meeting starts up again.

Cecilia: “So, what do we think about materials? Daniel, can you bring up the requirements specification?”

Daniel: “Sure, here it is. We said that cost was prioritized and that veneer, PET, and aluminum are the main candidates.”

Eva: “We have to remember what Sandra said about multiple disassembly cycles. Can all options manage that?”

Cecilia: “It’s doable, but it’s a lot more engineering involved if we go for the veneer.”

Daniel: “Yes, but we have to think about design longevity as well. The veneer would be nice since it is kind of timeless.”

Adnan: “And with veneer, I think we can get a good price from our supplier. I think they have spare time now, so we could probably get a good deal there.”

Eva: “That would be great! How do you know that?”

Benny: “We just have to make sure that this deal does not have us remaking the whole damn product again. Do you remember the chaos last time, Adnan or Eva?”

Adnan: “Eva, I heard it at the game last night. Their CEO was the referee.”

Cecilia: “Veneer would probably make it a little bit easier to incorporate 5G than aluminum, as well.”

Daniel: “Sure, but PET would be as easy, and we could try out the whole product in our lab then.”

“Hopefully, we’ll go for the veneer. It’ll be good to have a local supplier, and Sundin’s have always been a reliable partner,” Adnan thinks to himself. He reminds himself of the article in today’s newspaper about how the younger generation wants to stay in Hudiksvall but cannot find any jobs. But how many can Söndermarken employ? Probably not that many, unless Alpha becomes a bestseller. He shifts his focus back to the meeting.

Eva: “Okay, I’ll call Sundin’s tomorrow and ask for a price. But can we make it work?”

Benny: “We could probably make it work, but do you have an idea of what we need to change in the humidifier, Cecilia?”

Cecilia: “We have looked into it, and it seems like it isn’t that much. We need some new parts for the casing, and we need to redraw the earth, but it should not be a problem. Oh, and we need to move some buttons unless we go full smartphone right away.”

Adnan: “If we can get rid of the buttons, it would be great in production. They’re too finicky; we already have two workers that we need to find another job for. They break their fingers, lose their grips.”

Daniel: “I don’t think we can do that right away, but we are looking into including app controls.”

Eva: “The market isn’t really there right now; the customers just want something straightforward. At least in the Alpha price segment.”

Benny: “As I said, as long as we do not have to replace all electronics as well, it should be fine.”

The team decides to use birch veneer for the fascia panel.

In this scenario, Adnan draws from his personal identities both as an active member in the civil society and as a local patriot for the region to inform the decision and affect his preferences. He states explicit professional preferences (cost, ease of assembly, fewer workplace injuries), but he clearly has implicit personal preferences (local jobs, making sure other local companies can sustain their business in the region, assisting civil society).

6

6 Conclusions and contributions

When the research presented earlier was gathered and collectively analyzed, multiple conclusions were drawn from the research material. In this chapter, the author presents these conclusions and reconnects to the research questions presented in chapter 1. In order to fulfill the aim of the thesis (to explore how the decision-making process in product realization is done and if the tools and methods used today are suitable for helping developers make decisions), multiple studies on product realization were performed, where the author took on multiple different roles to explore material-related decision-making to its fullest extent. This exploration gave some novel insights on how decision-making regarding materials is done in product realization projects, confirming some established paradigms and highlighting the need for some activities both in the product realization process, and in education of designers and engineers. The main conclusions presented in this thesis are the following:

1. The multidisciplinary of material selection
2. The risk of rational decision-making
3. Changing the development process
4. Developers and their preferences
5. The need for a vision

The appended studies have contributed to the conclusions, as shown in Figure 18. As can be seen in the figure, all conclusions can be traced back to at least three studies, and all studies have contributed to at least two conclusions, showing the interconnected nature of the work presented.

Figure 18. Visual representation of how the appended studies have influenced the presented conclusions.

6.1 Conclusions

6.1.1 The multidisciplinary of material selection

The combination of factors affecting material selection and the introduction of new materials in a product realization process makes this a multidisciplinary field. The affecting factors can be broadly divided into three categories; human, technological, and organizational. Therefore, efforts to aid in introducing new materials should include human, technological, and organizational parts. An effort that only solves technological challenges will not be enough to aid the material selection process and, therefore, cannot be the only consideration when designing tools and methods for material selection. Developers working with this should also acknowledge the multidisciplinary and not treat the problem as a purely technical question of quantifiable parameters that should be aggregated and compared. This conclusion contributes to the answers to RQs 1 and 3.

6.1.2 The risk of rational decision-making

Entirely rational decision-making in product development is impossible or close to impossible due to the information need that contradicts the wicked nature of design problems. If one adopts a more classical engineering view on decision-making, rational decisions could be possible if all preferences are discussed. Selecting and introducing a new material will be neither rational in a classical engineering sense since the risks and costs are too high to be proactive in this decision, both personally, organizationally, technically, and financially. Traditional materials will be preferred if a rational (or assumed rational) decision-making process is implemented, resulting in no or incremental changes rather than radical change. The lack of information and knowledge regarding new materials will put these at a clear disadvantage if a rational model is implemented; the consequences of the decision cannot be imagined before the decision is made. This is especially true if the project is working according to risk-minimizing principles rather than opportunity-maximizing. This conclusion contributes to the answers to RQs 1 and 2.

6.1.3 Changing the development process

If new materials should be introduced and selected efficiently, we need to step away from the traditional engineering decision-making process. Rationality can still be a goal, but developers' personal preferences and the lack of data should be acknowledged as boundaries to rationality and taken into account in the design of the decision-making process. Since personal, human factors cannot be excluded from the process, these aspects of decision-making should be acknowledged in the further development of engineering decision-making. This is needed both from individual developers and project teams. This conclusion contributes to the answer to RQ 3.

6.1.4 Developers and their preferences

Developer preference, behavior, and habit need to be acknowledged in the product development process in general and the material selection process in specific. Assumptions that developers are merely vessels for information processing will make processes, methods, and tools less able to help find suitable solutions for new prod-

ucts and increase the risk of underutilizing new possibilities. Instead, what should be done is to make preferences, behaviors, and habits explicit and discuss how these affect the development work. Lindwall and Törlind (2018) have discussed this as a challenge for additive manufacturing; however, in this thesis, an argument is made for this being something to manage in all development processes that involve human developers. This conclusion contributes to the answer of RQs 1 and 2.

6.1.5 The need for a vision

The introduction of new materials needs an organizational material vision and mission statement to become a reasonable choice since the current processes discriminate against using new materials to risk-minimize. This means that there needs to be organizational slack, production capacity, and continuous learning within the organization. The organization needs to create the flexibility to introduce new materials both in development and in production. Combining a material vision, organization slack, and flexibility can lessen the effect of path dependency and make the organization more adaptive as new materials are industrialized. When formulating the material vision and mission statement, a structure of HTO (as was presented in 4.3) can be a suitable start. This conclusion contributes to the answer to RQ 3.

6.1.6 Reconnecting to the research questions

To connect the conclusions presented in 6.1.1-6.1.5 to the research questions presented in chapter 1, the author presents brief answers to the research questions. These answers do not fully convey the complexity of the conclusions presented in this work, but can be used to get a brief overview of the work.

RQ 1: How are developers interacting, mentally and physically, with the materials and the production process when developing a new product?

This interaction is highly complex, and could be described as partly a result of having mental models of materials and production processes. These draw from learned information, personal experience, professional identity, and many other factors that affect the mental models. This is further elaborated in chapter 4, and in sections 6.1.1, 6.1.2, and 6.1.4, and visualized in chapter 5.

RQ 2: What parts of decision theory and analysis could be relevant for product development in general, and material selection in specific, in order to develop new methods and tools for developers?

The acknowledgement of non-rational decision-making is both applicable and relevant to product development in general, and material selection in specific. Other factors to acknowledge, are the effects of identity (both personal and professional), ambiguity, and experience on decision-making. This is further elaborated in chapter 3.3 and 4, and in sections 6.1.2 and 6.1.4.

RQ 3: What can be done within this interaction between developer and material, to reduce the risk for failure when selecting materials and when using new materials in products?

There is a possibility to restructure the product realization process to take human decision-making into account, work actively with material visions, and work with flexibility to manage some of the uncertainties when introducing new materials in

products. This should reduce the risk for project failure due to material-related issues. This is further elaborated in chapter 4, and in sections 6.1.1, 6.1.3, and 6.1.5.

6.2 Contributions

Outside of the conclusions mentioned earlier, some main contributions can be outlined. These are defined as academic contributions, industrial contributions, and educational contributions.

6.2.1 Academic contribution

In this thesis and the appended studies, the author has shown the multiple levels of factors affecting material selection in product development; while technological factors have been traditionally acknowledged, there is also a need to understand human and organizational factors. This can contribute to the fields of tool and method development for product development and help understand how digitalization can be incorporated into the development process.

This thesis is also the beginnings of a theory of how mental models can be applied to developers' behavior in product realization projects to complement its use in HMI user research. This can contribute to future academic work on product development processes, design methodology, and product development tool design.

This thesis shows the use of design fiction as a visualizing tool for understanding certain behaviors in design work. Design fiction is still young as a research method, and this thesis can be used as an example of possible applications for the methodology.

6.2.2 Industrial contribution

In this thesis and the appended studies, the author has shown the complexities of material selection when developing new products. For industrial purposes, this thesis can be used to start to identify pitfalls and errors in the material selection process within a company, in the situation that the company identifies the lack of new material introduction as a risk for future profits.

The work presented in this thesis can also create a basis for internal investigations of organizational material flexibility, the ability to understand and implement new materials and identify bottlenecks for sustainable material use in products as a part of continuous sustainability work.

The research presented in this thesis also points towards the value of life-long learning in the industry. Since materials are developed continuously, there will be a need for developers to update their portfolios and to work with different types of materials throughout their careers. Suitable vocational education and industry-oriented academic courses could help with that and provide knowledge-sharing between experts in different fields.

6.2.3 Educational contribution

In the education of design and engineering students, there is a need to discuss the existence and effects of the students' personal preferences when designing products. These preferences will affect their decision-making, will be the result of their experience, education, and identity, and will evolve throughout their education and later careers.

In this thesis, the simplifications of tool and process descriptions in product realization are visualized. While these simplifications are valid and necessary, they need to be made explicit and emphasized when these tools and processes are taught in design and engineering education. This can be done in many different ways, where one can be to show a multitude of different options to show the differences in focus.

The author has also shown the complexity of sustainability in product development, focusing on material selection. If examples like these are used in education, junior developers can understand how complex these challenges are and hopefully avoid some fall pits and local optima's when encountering industrial challenges similar to these.

6.3 Future work – what is to come?

The author suggests a continued effort to understand how identities affect design work in future research. This work shows that they have an effect, but there is a need to understand if causal links can be made and how they can affect decision-making. If this can be done, it can be contributing to academia, industry, and education.

For future research, the author argues that it would be interesting to understand the role that alternative product development processes like Material Driven Design can play in sustainable development. Some of the fundamental underpinnings are promising, attempting to fully utilize a material's properties and create a public impression for new and novel materials. How can this be done so that it not only generates more products but also generates a better living with reduced use of resources? Furthermore, how can Material Driven Design and the like be implemented in a more traditional product-producing company?

The integration of non-rational aspects in decision-making is also an exciting topic. How can this be done in an environment striving for rationality (as engineering usually does)? How can these aspects be included in a process that involves explicit metrics and trade-offs, as well as more qualitative factors like product experience and aesthetics?

Since the work presented in this thesis has been centered mainly around two types of material (wood-derivates and metals, mainly aluminum), it would be interesting to broaden the scope and investigate these questions regarding more materials. The analysis was made to be as generalizable as possible, but other materials might change some of the outcomes and complement the body of knowledge. In the analysis chapter, CFRP is mentioned: the interconnectivity between production and material properties that is significant for some composites could bring in new aspects that the developers need to consider.

In some of this research, tools, and methodologies traditionally attributed to user research have been used to understand developer behavior and understanding. This is an exciting field since the developer could, in some sense, also be described as a user of the material and products developed (but from a completely different use case and standpoint). It would be of interest to further understand how these tools can be used to improve developer performance and what new tools can be developed to further understand the needs and requirements of the developer in order to develop better products and products in new materials.

On a more personal note, I would like to continue the work on understanding the human developer and their role in the development process, along with the behaviors of humans in the product development process. This work could complement the academic work on automation of parts of product development work (Amadori, 2012; Tarkian, 2012; Honarpardaz, 2018; Wehlin, 2021), by showing what goes into a product development decision and where humans have a decision-making edge over computing algorithms.

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Papers

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Any final words?

Funny you should ask ...

Jag tror att själ och hjärta

Är på väg tillbaka

Lars Winnerbäck (Själ och Hjärta)

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