THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

CHALMERS

A Systems Engineering Approach for Design of Production Systems for Novel Products

Proposition of a systems engineering framework combining Concept of Operations, Model-based Systems Engineering and creative cross-functional workshops to support powertrain production systems engineers when designing human-centric production systems for battery production

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Abstract

The heavy truck industry is facing new market challenges and is investing vastly in new product portfolios. Investments in the industrial systems are of significant magnitude, with annual costs for equipment and machinery in some cases more than double the costs for R&D.

Remarkably, despite the vast monetary investments made in production systems, the interest shown by industry and academy in systematic and effective systems engineering design methods in production system design is low. For the powertrain production system engineering community, there are several additional factors impacting simultaneously which are influencing the required skillsets and ways of working, for example the transformation to electric powertrains and the drive to build human-centric production systems. With systematic systems engineering, the risks with industrial projects of cost overruns, increased lead times and work overload for engineers due to late capturing of requirements could be reduced, and this leads to Claim 1 of this research:

- **Claim 1**: The synthesis of the current industrial problem and the research gaps indicates that a framework is needed for human-centric production system design for novel products in order to mitigate risks in terms of cost, performance and schedule due to late identification of system requirements.

Two large battery plant projects were followed for 18 months, starting in the concept phase. A Design Research Method was applied with workshops and interviews with a total of 178 practitioners (not 178 unique individuals, however). A framework was developed combining the systems engineering methods of Concept of Operations and Model-based Systems Engineering with creative cross-functional workshops and visual models. The framework is called Visual Design Human-Centric Production (VDHCP). By following the developed framework, 60 previously neglected new IT demands were identified. Additionally, the methods created engagement from engineering and project members. Traditionally, non-detected demands would have become obvious after implementation of the production system with potential consequential cost overruns, increased lead times and work overload for engineers. The findings of these studies lead to Claim 2 and Claim 3 of this research:

- **Claim 2**: The VDHCP framework, combining the system engineering methods of Concept of Operations and Model-based Systems Engineering with creative cross-functional workshops and visual models, could be developed to support powertrain production system design engineers to identify system requirements early when designing human-centric production systems for novel products.
- **Claim 3**: The VDHCP framework supports powertrain production system design engineers to identify system requirements early when designing human-centric production systems for novel products, as 60 previously neglected new IT demands were identified and hence mitigated the risks in terms of cost, performance and schedule due to late identification of requirements.

Recommendations for future work include exploring further what the production system design engineering community could harvest from the product development community, and if these methods would have any actual impact on project cost and lead time overruns, workload of engineers and better production systems in terms of resilience, sustainability and human factors.

Keywords: systems engineering, systems engineering design, electric powertrain, Concept of Operations, Model-based Systems Engineering, battery production, human-centric design

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“Standing on the shoulders of giants”. This is a phrase I didn’t fully understand when I began my PhD journey. I truly realise now what a vast community of created knowledge the world possesses.

Malin Hane Hagström
Gothenburg, Sweden, 2024

Appended Publications

The following publications are included in this thesis:

Paper A

Hane Hagström, M., Bergsjö, D., Sathyanarayana, A., Machado, C. (2023). "Visualising wastes and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations"

International Journal of Product Development (IJPD), Vol. 27, No. 3, 2023

Paper B

Hane Hagström, M., Bergsjö, D., Martinsson, H., Blomberg, J. (2022). "Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions"

International Journal of Product Lifecycle Management : IJPLM. - Genève : Inderscience Enterprises, ISSN 1743-5129, ZDB-ID 2205100-4. - Vol. 14.2022, 1, p. 70-101

Paper C

Hane Hagström, M., Bergsjö, D., Wahrén, H. (2023). "Drivers and barriers to implement digitalisation in engineering processes – a literature review".

Proceedings of the Design Society , Volume 3: ICED23 , July 2023 , pp. 737 – 746

Paper D

Hane Hagström, M., Bergsjö, D., (202X). "Using Concept of Operations to design human-centric manufacturing systems for novel products. A prescriptive study, Part 1."

In review to Journal of Systems Engineering (INCOSE)

Paper E

Hane Hagström, M., Bergsjö, D., (202X). "Using Model-Based Systems Engineering to design human-centric manufacturing systems for novel products. A prescriptive case study, Part 2."

In review to Journal of Systems Engineering (INCOSE)

Paper F

Hane Hagström, M., Bergsjö, D., (2024). "A Proposed Framework Using Systems Engineering To Design Human-Centric Manufacturing Systems For Novel Products To Reduce Complexity And Risk"

Accepted to DESIGN 2024 Conference

Work distribution in the appended papers

Paper A

Sathyanarayana, A. and Machado, C. performed the data collection under the supervision of M. Hane Hagström. The planning, analysis and writing of the paper was conducted by M. Hane Hagström. D. Bergsjö contributed constructive criticism during the writing process.

Paper B

Martinsson, H. and Blomberg, J. performed the interviews under the supervision of M. Hane Hagström. The planning, analysis and writing of the paper was conducted by M. Hane Hagström. D. Bergsjö contributed constructive criticism during the writing process.

Paper C

Malin Hane Hagström, M. was the lead author and orchestrated writing, data collection and analysis of data. Bergsjö, D. contributed through planning, supervision and editing of the paper. Wahrén, H., collected first sets of data and coded the data in NVivo.

Paper D

Malin Hane Hagström, M. was lead author and orchestrated writing, data collection and analysis of the data. Bergsjö, D. contributed through planning, supervision and editing of the paper.

Paper E

Malin Hane Hagström, M. was lead author and orchestrated writing, data collection and analysis of the data. Bergsjö, D. contributed through planning, supervision and editing of the paper.

Paper F

Malin Hane Hagström, M. was lead author and orchestrated writing, data collection and analysis of the data. Bergsjö, D. contributed through planning, supervision and editing of the paper.

Other related publications by the author not included in this thesis:

i. Adriana Ito, Dan Li, Malin Hane Hagström, Jon Bokrantz, Anders Skoogh, Maja Bärring, Johan Stahre (2023). A Collaborative Digital Platform for Root Cause Analysis in a Value Chain. Advances in Transdisciplinary Engineering, 35: 299-307. http://dx.doi.org/10.3233/ATDE230056

ii. Eckert, C., Isaksson, O., Hane Hagström, M., and Eckert, C. (2022). "My Facts Are not Your Facts: Data Wrangling as a Socially Negotiated Process, A Case Study in a Multisite Manufacturing Company." ASME. Journal of Computing and Information Science in Engineering. December 2022; 22(6): 060906. https://doi.org/10.1115/1.4055953

iii. Hane Hagström, M., Bergsjö, D., Furborg, F., Aas, R. (2022). "Comparing the quality of documentation used in production equipment acquisitions and the impact on the performance of the acquired equipment – a pre study". DS 118: Proceedings of NordDesign 2022

iv. Adriana Ito, Malin Hane Hagström, Jon Bokrantz, Anders Skoogh, Mario Nawcki, Kanika Gandhi, Dag Bergsjö, Maja Bärring (2022). "Improved root cause analysis supporting resilient production systems". Journal of Manufacturing Systems,Volume 64,Pages 468-478, ISSN 0278-6125,

v. Eckert, C., Isaksson, O., Eckert, C., Coeckelbergh, M., and Hane Hagström, M. (2020). "Data Fairy in Engineering Land: The Magic of Data Analysis as a Sociotechnical Process in Engineering Companies." ASME. Journal of Mechanical Design. December 2020; 142(12): 121402.

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1. Introduction

In this chapter, the background with specific challenges and transformational drivers for the powertrain production system engineering community are elaborated on. The research focus addressing the industrial problem and research gaps is presented, followed by the corresponding research questions.

The heavy truck industry is facing new market challenges. A market report from 2023 by McKinsey & Company states that five core trends are transforming commercial vehicle sales: the growth of omnichannel sales, new value pools and business models, increasing cost pressures, stringent regulations with the shift to zero-emissions vehicles (ZEVs), and the emergence of new entrants (Dau et al., 2023). To meet the challenges, the industry is investing vastly in new products. For example, the global actor IVECO is concluding its biggest investment cycle ever with the launch of a completely renewed product and service offering (ivecogroup.com, 2023), and another competitor, Volvo Trucks, is unveiling an all-new heavy-duty truck platform for the North American market in parallel to a new heavy-duty truck range for Europe, Australia and markets in Asia and Africa (volvogroup.com, 2024). Unsurprisingly, the R&D expenses for Volvo Group (2021, 2022, 2023, 2024) and Scania Group (2021, 2022, 2023), also well established in the market, have grown steadily to new record levels since 2021, in some cases almost doubling their budget. Further analysis of the actors' annual reports shows that costs of property, plant and equipment is in Volvo Group's case moving from 49 BSEK in 2020 to 68 BSEK 2023, while Scania Group is showing similar evolution for machinery and equipment with costs in 2020 at 46 BSEK to 55 BSEK 2022. The evolution in R&D investments 2021 to 2023 for Volvo Group, Scania Group and IVECO group, together with cost evolution for equipment and machinery for Volvo Group and Scania Group, is described in Figure 1.

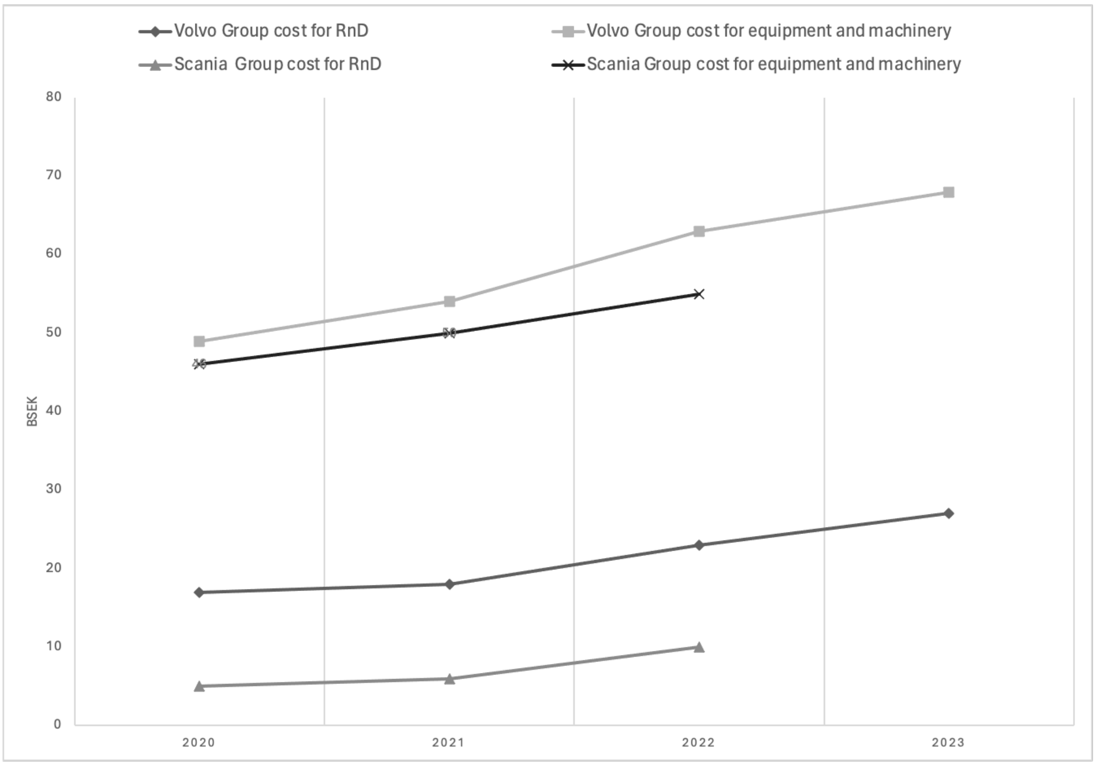


Figure 1: Evolution in R&D investments and costs for equipment and machinery for Volvo Group and Scania Group (Annual reports 2021, 2022, 2023, 2024).

Furthermore, investments in the industrial systems are of significant magnitude. For example, Volvo Group invested 16.6 BSEK in 2022 and IVECO is planning to invest 1,000,000 mEUR in the industrial system in 2024.

Remarkably, despite the vast monetary investments made in production systems, the running costs that they entail, and the fact that these systems are often kept in operation for decades, the interest shown by industry and academy in systematic and effective systems engineering design methods in production system design is low. At the same time, the focus on applying design methods for *end-user products* has received considerable attention, both from academia and industry, with concepts like Design Thinking, Lean Product Development, Agile etc. (Wynn & Clarkson, 2018).

The importance of design, in particular as an industrial activity, and the increasingly complex and dynamic context in which it takes place, has led to the desire to improve the effectiveness and efficiency of design practice (Blessing & Chakrabarti, 2009). As described by Munro (1989) "product design may only account for five percent of a product's total cost, but it dictates seventy percent of the product's total cost. Therefore, it becomes critical that designs are done right, the first time". Figure 2 describes share of total product cost versus level of influence on total product cost from Munro.

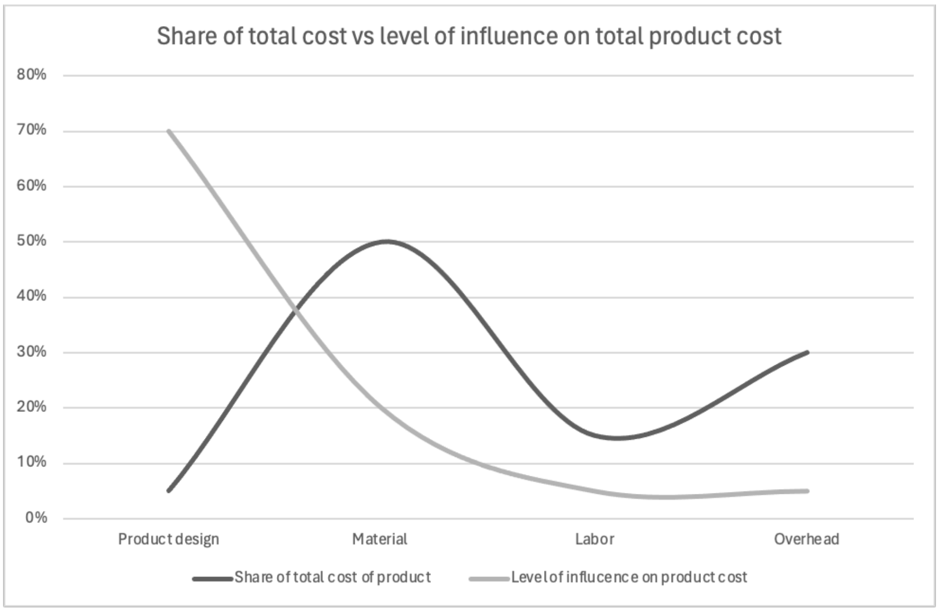


Figure 2: Share of total cost vs level of influence on total product cost from Munro (1989)

As described by Pahl and Beitz (1996), "every design task involves certain constraints (…) which must be fully understood if the optimum solution is to be found". They continue: "designers must define the task as fully and clearly as possible so that amplifications and corrections during its subsequent elaboration can be confined to the most essential". From tools described in, for example, IATF16949 (2016) it is learned that the cost of developing countermeasures to detected failure modes varies largely depending on when in the product life cycle the failure mode was detected, as illustrated in Figure 3.

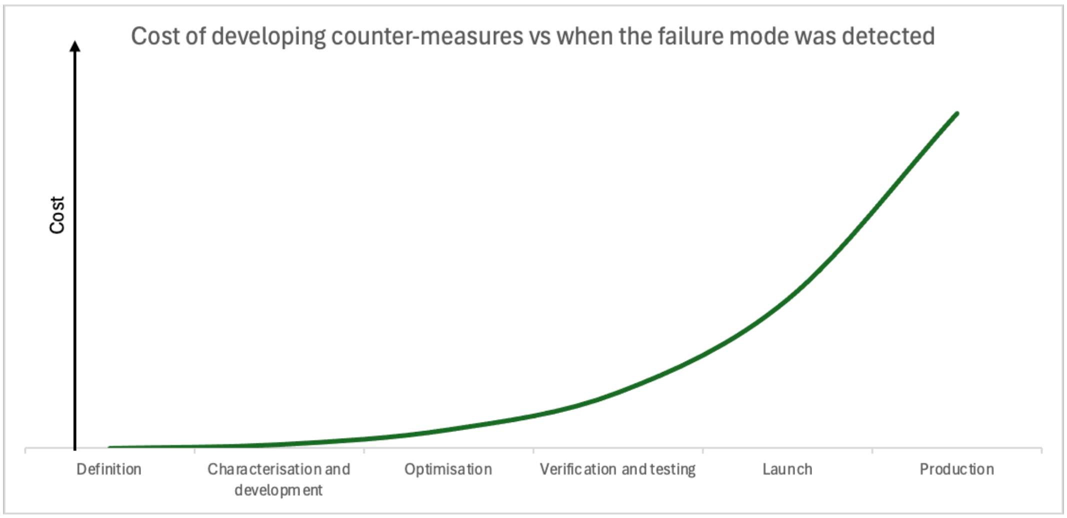


Figure 3: The cost of developing countermeasures to detected failure modes varies largely depending on when in the product life cycle the failure mode was detected (from IATF 16949APQP)

Hence, considering the production system as a product, the same logic applies to the design of production systems:

- The major part of the costs of the production system is defined in the design of the production system.
- As the production systems has such economical magnitude, amplifications or corrections of the production system design in late stages will have significant financial impact.

Efficient production systems are necessary for the realisation of products that fulfil customer needs and delivery requirements (Bellgran, 2003) (Ito et al., 2022). Bellgran continues: “Designing a production system is a unique and complex task in which many parameters should be taken into account during the process of creating, evaluating and selecting the proper alternative”. One important activity in the design of production systems is the acquisition of industrial equipment. In the automotive industry this equipment, especially for the machining process, become complex with a high purchase value, and hence the ambition is to focus on the equipment having a long lifetime while being as efficient as possible.

De Weck et al. (2011) point out that “Today, working in an engineering system, that same engineer has to interact with a host of socioeconomic complexities and ‘externalities’ – impacts, either positive or negative, that are not a direct part of the artifact or even a self-contained system or process under consideration.” Engineering is a knowledge-centric activity (Natarajan et al., 2019). Natarajan et al. (2019) mention that “as engineers, we manage complexity operationally by using our (partly tacit) understanding by creating overall system models, multiple domain-specific models and views and maintaining and managing consistency among all of them”. This means that for effective systems engineering design, managing knowledge is key. At the same time, engineering is also a process and a social practice, involving various social actors who have specific roles in the practice and act at different stages in the process. The importance of production system capabilities is increasingly acknowledged.

However, the process of designing the production system has received little academic attention, ignoring its potential for gaining a competitive edge (Bellgran & Säfsten, 2009; Bruch, 2012).

Bruch states: “Designing production systems in an effective and efficient manner is advantageous as it supports the possibility of achieving the best possible production system in a shorter time”. Islam et al. state that “there is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap” (Islam et al., 2020). Vielhaber and Stoffels identified that in academia there is a greater focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts (Vielhaber & Stoffels, 2014).

As described in the Systems Engineering Handbook by NASA, the objective of systems engineering is to see that the system is designed, built, and can be operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk (Kapurch, 2010). The hypothesis presented in this thesis is that since production systems entail significant costs for a considerable future, are highly invested in but designed in less systematic ways, there is potential to apply systems engineering methods developed in the design community to a larger extent for design of production systems.

1.1. Background

Product development methods have been explored and adapted over many years. Within the systems engineering (as well as the engineering design) community, several methods have been developed to reduce complexity and manage risk from engineering institutions such as NASA (Kapurch, 2010) and INCOSE (2020) as well as key researchers in the field (Ulrich et al., 2020). However, these methods have not yet been fully adopted by the manufacturing engineering community (Arista et al., 2023). Arista et al. state that “only parts of the design process knowledge are captured explicitly using different documentation approaches and very little information persists from one design to another. Designers take decisions based on their assessment and experience”. Stark et al. (2017) take a similar view: “Interlinked and autonomous manufacturing systems provide new opportunities in smart manufacturing. Today’s manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity”. Stark et al. continue: “In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity”. The industrial part of product development projects is highly complex, carries significant risks, and represents considerable levels of investment. For some reason, these types of projects are managed in less mature ways than their counterparts on the product side.

1.1.1. Specific challenges to the powertrain production system engineering community

From observing the powertrain production system engineering community from within, there are several additional factors impacting simultaneously which are influencing the required skillsets and ways of working. While there are numerous other factors that could influence, a selection of these identified external transformation drivers are elaborated on further in five factors.

a) *The movement from combustion engines to electrified vehicles.*

Regarding the <u>*new end-products*</u>, Denger and Zamazal (2020) state that “new features and functionalities as well as the increasing share of electrics/electronics and software increase the system complexity, not to mention automotive trends such as electrification, autonomous driving and connected and frequently updated vehicles" is a major challenge facing modern manufacturers. There is a strong push from society towards sustainable solutions resulting in rapid transformation from fossil-fuel powered drivelines to electric. The powertrain industry in the truck market segment needs to develop business models, solutions and products that are completely new and unexplored. External market reports show that the global electric truck market is forecast to reach 1,500,000 units by 2025, from less than 100,000 in 2013 (P&S Intelligence, 2018) (P&S Intelligence, 2023). The combustion engine is more than 100 years old and has served as the heritage and knowledge base for the entire powertrain engineering community, both for product development and for the production system used to produce these products. The production system that is now required to produce the electric drive-lines has completely different characteristics and the knowledge needs to be created for the engineering community. The dominant production processes for combustion engines have traditionally been forging steel, machining the steel with high precision and then assembling external parts onto the steel, to a large extent manually. With electrification, the battery is the central part, with the main challenges today being to reduce the battery's size and cost. Other top challenges mentioned by Denger and Zamazal are time-to-market goals, low innovation rates together with increase in product quality and product lifecycle cost control. All these challenges will have significant impact on the manufacturing engineering processes.

b) *The movement of production equipment from an Industry 3.0 technology to an Industry 4.0 technology level.*

Regarding the *equipment*, Industry 4.0 is transforming manufacturing systems. A market report from Fortune Business Insights in 2021 projects that the European Industry 4.0 market will grow from $116 billion in 2021 to $337 billion in 2028 (Insight, 2021). Industry 4.0 is described as the fourth industrial revolution, the first being the invention of the steam engine, the second the invention of electrical motors and the third when computers and the internet came into our lives. The fourth industrial revolution comes with automation and computers coming together with "the internet of things" and big data analysis (Boone, 2020), and towards enabling the usage of internet of things with collaborative and proactive solutions (Bokrantz et al., 2017). When in place, the Industry 4.0 factory should have developed into an intelligent environment where the system of production equipment is exchanging information, triggering actions and controlling each other autonomously (Weyer et al., 2015). It is evident that machines will be performing more complex tasks and require higher uptimes, which will put high demands on designing the production system, on acquiring the machines and on having the ability to maintain them. This will presumably lead to an increased amount of automation in factories, together with information about everything from quality of end-products to what maintenance might be needed for the production equipment (Li et al., 2019), to name a few examples. Another paradigm shift is the transition to a circular economy. Circular economy is considered an innovative approach used to increase the resource efficiency in companies by keeping equipment functioning for as long as possible (Wakiru et al., 2018). This implies that society needs to become better and better at designing for sustainability, which means then designing for maintainability.

c) *The reduced levels of performance in production system design*

When studying the *state of practice* of a manufacturing firm to address equipment break-down issues already in the production equipment acquisition phase (Hane Hagström, 2021), the data shows that maintenance of new machines continues to be an issue for the case company and could possibly also be an increasing issue. The maintenance cost is increasing by between 59%, 12% and 18% each year in the initial life of the machine. To evaluate the effectiveness of the acquisition process, the data shows that machines that have been purchased recently have a higher maintenance cost factor. The findings support the theories that the design process is becoming less effective; but could also mean that the machines purchased recently are more complex to operate and maintain. The data shows that design weakness, meaning a problem with the machine that is due to the design of the machine, is at a high level and continues to be. There are numerous potential reasons for this, such as increased workload of the engineers, increased complexity of the machines or increased complexity and globalisation of the supplier base; but it indicated that there is an opportunity for increased awareness and knowledge of maintenance aspects in the design phase. Earlier studies in the case company (Blomberg & Håkansson, 2019) have shown that the success of design projects in terms of fulfilment of expected properties is only monitored, in the best of cases, for one year. There is a potential to follow the performance of the equipment for a longer period to detect the true issues and feedback to the design process as learnings from production. Earlier studies in the case company have also shown that the design guidelines are more of procedural guidelines on a macro level and could benefit from moving to a more analytical micro level of guidelines to support knowledge creation and reuse further (Blomberg & Håkansson, 2019).

d) Growing levels of automisation in office work

The impact of automisation and digitalisation on the *engineering process itself* could be vast with for example the introduction of artificial intelligence in white collar domains. Society is demanding shorter development cycles and increased resource efficiency (Lasi et al., 2014). “Interlinked and autonomous manufacturing systems provide new opportunities in smart manufacturing. Today’s manufacturing system design processes and architecture still are based on traditional engineering methods and can hardly cope with increased system complexity” (Stark et al., 2017). Lasi et al. (2014) state that “The term ‘Industry 4.0’ describes different – primarily IT-driven – changes in manufacturing systems. These developments do not only have technological but furthermore versatile organizational implications. As a result, a change from product- to service-orientation even in traditional industries is expected”.

e) Demands on human-centric production systems prepared for Industry 5.0

Industry 5.0 is described as “the movement to bring the human touch back to the manufacturing industry” or to “leverage the unique creativity of human experts to collaborate with powerful, smart and accurate machinery” (Akundi et al., 2022). Governmental institutions are starting to explore the concept in several publications, for example the European Union (M. Breque et al., 2021). Industry 5.0 complements the techno-economic vision of the Industry 4.0 paradigm by emphasising the societal role of industry. It can enhance the quality of production by assigning repetitive and monotonous tasks to robots/machines and the tasks requiring critical thinking to humans (Maddikunta et al., 2022), decrease emphasis on technology and assume that potential for progress is based on collaboration between humans and machines. Communication and employee motivation are boosted by resulting in interactive knowledge environments (Adel, 2022). Industry 5.0 is revolutionising the manufacturing systems across the globe by taking away repetitive tasks from human workers. The consequences of Industry 5.0 will impact the production system engineering community.

These five drivers are summarised in Figure 4.

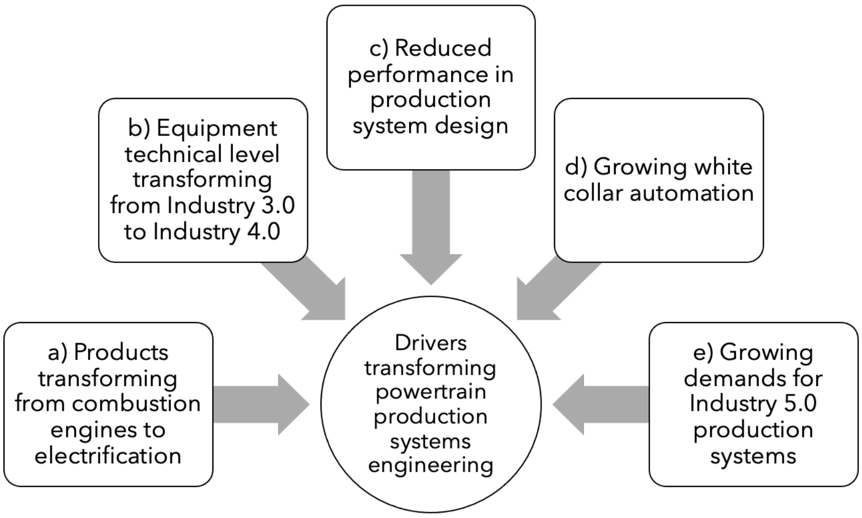


Figure 4: A summary of transformational external drivers for powertrain production system engineering community

1.2. Research focus

This content of the work in this thesis is in the field of Engineering Design Research. As such, it follows a two-fold research approach (Eckert et al., 2003) that seeks to *support engineering design practice* by providing new methods that improve production system design engineering for human-centric systems for novel products in the specification and concept development phase, and also to *generate knowledge* about the potential to use systematic and effective systems engineering design methods in production system design which includes the human aspects. As a result, the research seeks to contribute to solving an industrial problem and to closing a research gap.

1.2.1. Industrial problem

Considering the vast amounts invested in production systems, the running costs that they entail, and the fact that these systems are often kept in operation for decades, the interest shown by industry in systematic and effective systems engineering design methods in production system design is relatively low. This fact, together with the five identified transformational drivers for the powertrain production system engineering community, creates risks for heavy truck industrial projects in terms of cost, performance and schedule due to late identification of requirements on the system. Examples could include cost overrun during development, risk of delivering a system that does not satisfy the needs when in use, resulting in late and expensive adjustments, unsatisfactory performance and poor work environment. As systems engineering methods aim to mitigate exactly these risks, it is critical for industry to apply such methods in order to design, build and operate production systems that accomplish the purpose safely in the most cost-effective way possible.

1.2.2. Research gap

The process of designing the production system has received little academic attention, ignoring its potential for gaining a competitive edge (Bellgran & Säfsten, 2009; Bruch, 2012). Islam et al. state that “there is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap” (Islam et al., 2020). Vielhaber and Stoffels identified that in academia there is a larger focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts (Vielhaber & Stoffels, 2014). From the studies mentioned above, two research gaps are formulated:

- Research gap 1: Lack of systematic and effective systems engineering design methods in production system design.
- Research gap 2: Lack of inclusion of human aspects in the production system design.

The research gaps are further elaborated on in chapter two.

1.2.3. Research questions

The following research questions (RQs) were formulated to structure the research. RQ1 was formulated at the beginning of the research process, RQ2 and RQ3 were developed during the research, and RQ4 was developed from learnings gained from RQ1, RQ2 and RQ3.

RQ1: What is the current systems engineering state of practice in designing human-centric production systems?

Considering the vast amounts invested in production systems, the running costs that they entail, and the fact that these systems are often kept in operation for decades, understanding current production system engineering state of practice is fundamental to ensure the problem is real and not only a hypothesis. This research question aims to identify and analyse the current abilities in industry to apply systems engineering methods when designing production systems, both from the case company and from literature.

RQ2: How can the systems engineering methods of Concept of Operations and Operational Concept be used to reduce complexity and risk in the design of a human-centric production system for novel products?

A ConOps/OpsCon is a user-oriented document that describes a system's operational characteristics from the end user's viewpoint. It is used to communicate overall quantitative and qualitative system characteristics among the main stakeholders. ConOps/OpsCon can be considered as a transitional design artefact that plays a role in the requirements specification during the early stages of the design and involves various stakeholders (Kaasinen et al., 2022; Madni & Orellana, 2018). When completed, the ConOps/OpsCon can be presented with different levels of detail so that, by zooming in and out of the hierarchy, different elements of the system come into focus, and is a boundary object promoting communication and knowledge sharing. The research question aims to test the potential in using this method to reduce complexity and risk.

RQ3: How can the systems engineering methods of Model-based Systems Engineering be used to reduce complexity and risk in the design of human-centric production system for novel products?

The increase in complexity of modern systems results from the number of system elements and the amount of information and knowledge needed to describe the system (Madni & Purohit, 2019). Systems Engineering is an approach to handle the increasing complexity and is frequently associated with document-based engineering (Berschik, 2023). To overcome the challenges of document-based SE, MBSE shifts the focus to more formal modelling and the integration of different views into a consistent system model. Models are central to documenting results, applying simulations, analysing different solutions, and transferring knowledge in different engineering activities. When engineering modern systems involving services and subsystems from various engineering domains, different perspectives have to be addressed *resulting in a heterogeneous model landscape (Kattner et al., 2019). The research question aims to test the potential in using this method to reduce complexity and risk.*

RQ4: How could a systems engineering framework to design human-centric production systems for novel products to manage risk and complexity be designed?

This research question aims to mitigate the industrial challenges summarised in five main transformational drivers, as there is a need to develop Design Support for the powertrain production system engineering community. By developing this Design Support, the following Engineering Design Research targets are addressed: support engineering practice by providing new methods and generate knowledge about the potential.

1.2.4. Scope and delimitations

Almost everything people interact with these days is a product of some sort and hence the result of a product development process. The work in this thesis is concerned with the development of powertrain production system design. Therefore, the term “design” is used as in “engineering design” and not to be confused with graphical, industrial, or fashion design. The term “product” can include, beyond physical artefacts, software, electronics, and services. However, the work presented in this thesis is concerned with viewing the “product” as the production system as a cyber-physical entity. “Production” and “manufacturing” are used interchangeably. As stated by Bellgran and Säfsten (2010), “production system is often used as synonymous with manufacturing system”.

Cyber-physical systems (CPS) are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its ongoing processes, providing and using, at the same time, data-accessing and data-processing services available on the internet (Monostori, 2014).

The product development process spans a wide array of stakeholders, activities, and phases. The work in this thesis focuses on the activities in the specification and concept development phase (Stoffels et al., 2021). In this phase, the high-level needs of enterprise and business are developed, analysed and transformed to business and stakeholder requirements, whereas models of electrics, software, or the product life cycle are not directly considered. Furthermore, the focus is on the activities of capture, storage, and representation of production system knowledge from a human-centric perspective. Technical product or equipment details, life cycle concepts and acquisitions are not actively considered. The researched activities in this phase are influenced by many parameters, such as administrative, organisational, and cultural aspects. However, the research claims only focus on the application and use of systems engineering to design production systems for electric powertrain products to mitigate risk due to late identification of system requirements.

The scope of the research is novel products and production systems to be able to capture the distinction from developing a production system where both the process and the product concepts are original designs (Pahl & Beitz, 1996), to develop a production system where both of them are novel to the engineering community.

The Technology Readiness Level (TRL) scale was introduced in EU funded projects in 2012 and is currently the point of reference for determining the development or maturity of a research area and its potential and market-readiness (EURAXESS, 2024). TRL is useful to indicate the research project result’s level and define what steps should be taken in order to bring the research result to the market. The TRL approach has been used on and off in NASA space technology planning for many years. Since the research presented in this thesis was subject to time and resource constraints, the presented method has only been developed to approximately technology readiness level (TRL) 4 (“validation in laboratory environment” (Mankins, 1995) (Clausing & Holmes, 2010), and the tool used for demonstration, testing, and validation has only been developed to TRL 3 (“proof of concept”). However, no official TRL assessment has been performed. This approximate assessment has been done based on reading Mankins (1995). The data leading to the content presented in this thesis was collected at a single company.

2. Frame of reference

In this chapter, the underlying theories and accompanying subjects that will support the research are presented.

Coming back to the introduction, the objective of systems engineering is to see that the system is designed, built, and can be operated so that it accomplishes its purpose safely in the most cost-effective way possible considering performance, cost, schedule, and risk (Kapurch, 2010). The hypothesis of the work presented in this thesis is that since production systems entail significant costs for a considerable future, are highly invested in but designed in less systematic ways, there is potential to apply systems engineering methods developed in the design community to a larger extent for design of production systems.

To understand the theoretic framework of systems engineering, the topic is framed from a product development and engineering design perspective. Within systems engineering, the subtopic of production systems design is studied to be able to understand and evaluate the production systems design capabilities. The selected concepts and methods within these vast research areas are Design Thinking, human-centric systems engineering, Concept of Operations and Model-based Systems Engineering. From a context point of view, the production systems, the focus of the frame of reference is on cyber-physical production systems where the ambitions from Industry 4.0 and Industry 5.0 are specifically studied. The frame of reference areas of research contribution are presented in Figure 5.

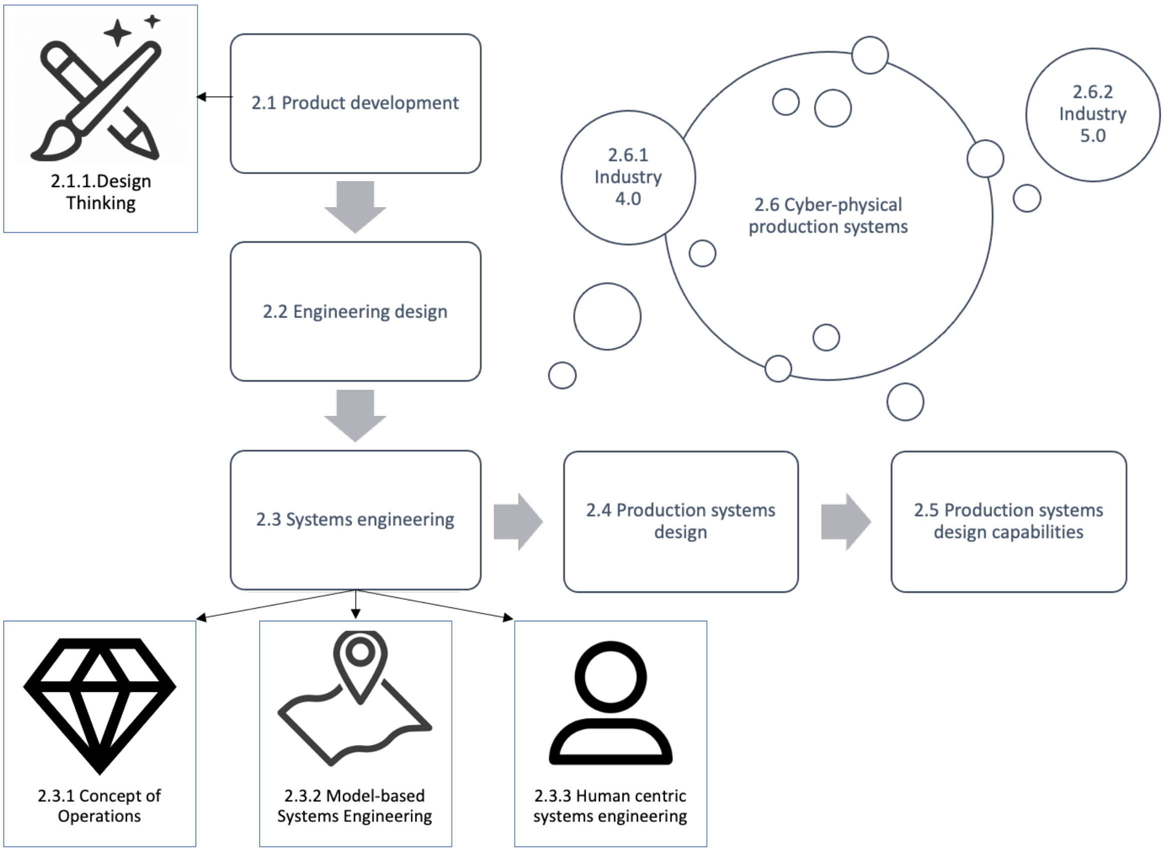


Figure 5: The frame of reference areas of research contribution, describing the main theoretical areas, the concept or methods selected and contextual topics selected.

2.1. Product development

The work presented in this thesis refers to the product development phases as presented by Ulrich et al. (2020), shown in Figure 6.

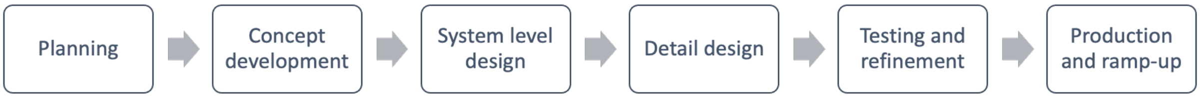


Figure 6: Phases of the product development process, after Ulrich et al. (2020)

In this framework, development is defined as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product", whereas design is defined as "defining the physical form of the product to best meet customer needs, including engineering design (mechanical, electrical, and software)". Pahl and Beitz (1996) use the term design synonymously for design and development. They continue by stating that the task and activities of designers are influenced by the several characteristics, for example the level of novelty. As stated by Chakrabarti et.al (2003), "novelty is defined only in relation to the knowledge base available in a given domain, i.e., we define the novelty of a new product relative to the existing products available as reference".

Ulrich et al. describe each product development phase in a generic level:

1. *Planning:*
   This phase precedes the project approval and launch of the actual product development process and begins with opportunity identification guided by corporate strategy and includes assessment of technology developments and market objectives.
2. *Concept development:*
   In this phase, the needs of target markets are identified, alternative product concepts are generated and evaluated, and one or more concepts are selected for further development and testing.
3. *System-level design:*
   This phase includes the definition of product architecture, decomposition of the product into subsystems and components, preliminary design of key components and allocation of detail design responsibility to both internal and external resources.
4. *Detail design:*
   This phase includes the complete specification of the geometry, materials and tolerances of all of the unique parts in a product and the identification of all standard parts to be purchased from suppliers.
5. *Testing and refinement:*
   This phase involves the construction and evaluation of multiple preproduction versions of the product.
6. *Production ramp-up:*
   In this phase, the product is made by using the intended production system. The purpose is to train workforce and resolve any remaining problems in the production processes.

The development of a production system follows these steps as well, and the work presented in this thesis focuses on the ability to follow the steps in design for production with the aim of designing for reliability. When applying the model above and focusing on production design and development of the production equipment, Figure 7 describes the critical deliverables for each phase.

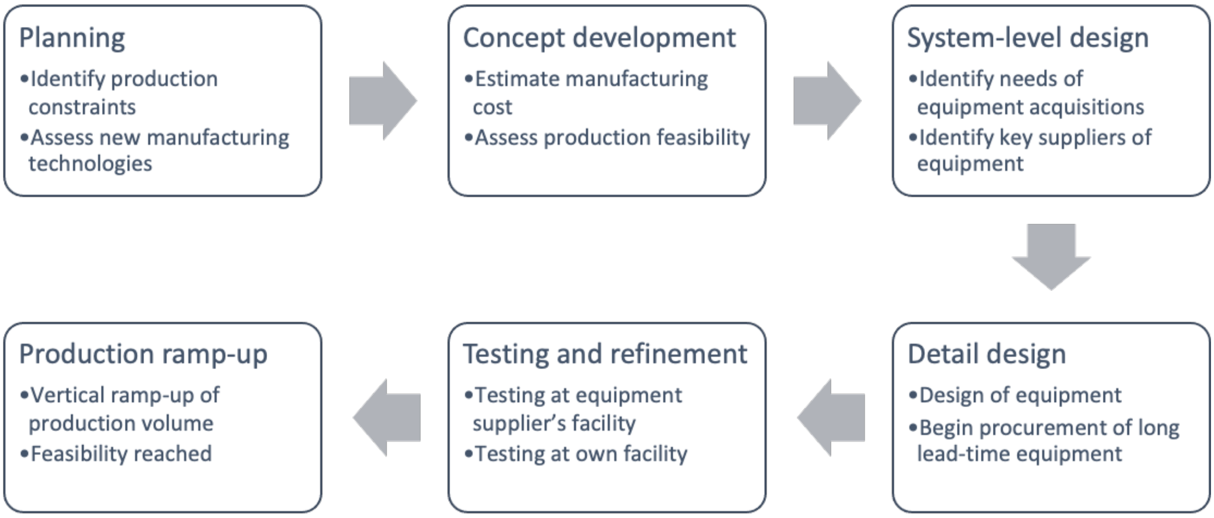


Figure 7: Critical deliveries in the product development phase regarding design and development of the production system equipment. From Ulrich et.al. (2020)

Ulrich et al. (2020) state that one major challenge of the product development process is to transfer a tremendous amount of information and knowledge within and between development teams. Other challenges in traditional product development models usually lead to a number of problems commonly seen in companies, some of which are: (i) work overload of designers and engineers who frequently perform unnecessary tasks, (ii) models that are not clearly understood by designers, (iii) project cost overruns, (iv) difficulty in retrieving knowledge from previous projects, and (v) ambiguity regarding tasks' responsibilities due to insufficient commitment of functional departments (Tortorella et al., 2016). When applying the lean philosophy in design, the main principles are the same but the application differs. There have been many efforts to define Lean Product Development more precisely (Tortorella et al., 2016) and several definitions exist. Ward (2007) defined Lean Product Development as "a set of operational value streams that should be designed to consistently execute product development activities effectively and efficiently, creating usable knowledge through learning. The building blocks of such value streams and knowledge creation cycles are organised along five principles: value focus, entrepreneurial system designer, teams of responsible experts, set-based concurrent engineering and cadence (pull and flow)." The term "usable knowledge" is defined as the value-adding part of lean product development. This means that for the design of the production system, it is critical to focus on the knowledge creation in the design process to enable the production system to support the lean principles of production.

The outlook for product development and engineering design will be affected by societal development. Isaksson and Eckert (2020) state that the climate crisis, new product technologies and new design technologies will heavily impact the design community by 2040. They describe further that circularity principles will become mainstream with scarce material resources, products will involve much greater integration between mechanical and connected software parts, and that artificial intelligence and simulation possibilities will open up possibilities in design behaviour in very early phases of development. Briard et al. (2023) elaborate on the possible impact of data in the product development phase; that data is used to identify new opportunities, support decision-making and reduce development time. Briard et al. also state that the research in this topic is still in its infancy. Open innovation is another angle on potential development of the design processes, where partnerships outside the organisation are co-developing in order to achieve new ideas, innovations, and manufacturing technologies (Rahmanzadeh et al., 2020). These shifts in society will not only have technological implications in product development, but also in organisational and management aspects such as team structures, project management, black box engineering and partnership involvement (Isaksson & Eckert, 2020).

2.1.1. Design thinking

Design thinking (Cross, 1984; Rowe, 1991) is a concept that started to gain attention academically in 2006 (Micheli et al., 2019). Despite the interest in the concept, there are differing views on what the concept entails. Some authors consider it more as an organisational trait while others view it more as individual traits (Brown & Katz, 2011). Some scholars focus more on the tools (Seidel & Fixson, 2013) while others view design as a culture (Elsbach & Stigliani, 2018). Some authors consider design thinking to be a part of design practice offering less additional value, that the concept is already included (Carlgren et al., 2016), or regard it as more of a management buzzword (Liedtka, 2015). According to Purdy and Popan (2023), “design thinking is a thought process that depends on examining all sides of an issue from both a practical and a creative perspective in a (…) solution-focused thinking”. They continue: “the major aspects of design thinking are understanding the practical and emotional needs of a client, using prototypes or physical models to explore possible ways of achieving goals”. Micheli et al. (2019) identify the principal attributes of design thinking in Table 1 from a systematic literature review:

Table 1: Principal attributes and essential tools and methods of design thinking, from Micheli et al., 2019

Attributes:
Creativity and innovation
User-centeredness and involvement
Problem solving
Iteration and experimentation
Interdisciplinary collaboration
Ability to visualise
Gestalt view
Abductive reasoning
Tolerance of ambiguity and failure
Blending analysis and intuition

Tools and methods:
Ethnographic methods
Personas
Journey map
Brainstorming
Mind map
Visualisation
Prototyping
Experiments

2.2. Engineering design

Engineering design research has been defined as “the study of principles, practices and procedures of design” (Cross, 1984) or as “the process of solving technical problems within requirements and constraints to create new products” (Pahl & Beitz, 1988). The main task of engineers is to apply their scientific and engineering knowledge to the solution of technical problems and then optimise those solutions within the requirements and constraints set by material, technological, economic, legal, environmental and human-related considerations (Pahl & Beitz, 1996). Figure 8 describes the central activity of engineering design from Penny (1970).

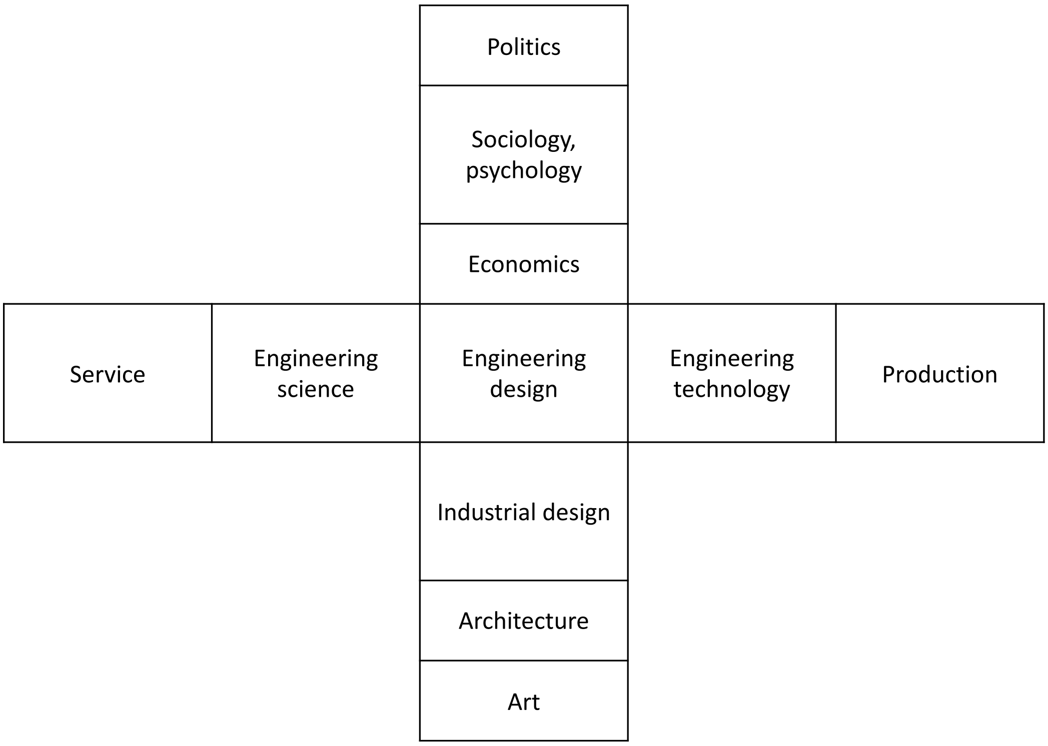


Figure 8: The central activity of engineering design, from Penny (1970).

Whereas engineering design is traditionally seen from a physical product perspective, Pahl and Beitz (1996) continue that "design tasks related to production machines, jigs and fixtures and inspections equipment (…) fulfilling the functional requirements and technological constraints are equally important". They also mention that it is important for a systematic methodology to be in place to ensure that designers reach potential solutions quickly and directly, and that it is important for design methodology to foster and guide the abilities of designers and encourage creativity while simultaneously focusing on the need for objective evaluation of results. Systematic design aims to rationalise the design and production processes.

Pahl and Beitz (1996) also discuss design for production, the purpose of which is to design the product in a way that minimises production costs and times while maintaining the required quality of the product. The importance of equipment performance is stated as a potential cause of changes to performance, failures and dangerous situations which can substantially reduce functionality, economy and safety. Sudden breakdowns disrupt normal operations and, because they are unexpected, involve considerable cost to rectify. Design for ease of maintenance is mentioned as a concept in itself. From an engineering design perspective, maintenance requirements should be included in the requirements list, and stated examples are variants that require minimal servicing, easily exchanged components and use of components with similar life expectancies. A technical solution should, in principle, require as few preventive measures as possible. The aim is complete freedom of service by using components of identical life, reliability and safety.

The discipline of ED has undergone several changes in the past decades, which have preceded or followed advances in manufacturing capabilities (Chiarello et al., 2021). Increased competition and increase in manufacturing digitalisation with new means to collect data on product characteristics, product performance and customer requirements, engineering design is now often accompanied by big data (Wang & Alexander, 2015)). However, Chiarello et al. mention that there is still a lack of data-driven approach in engineering design, as well as excessive focus in literature on the use of specific data modelling methods rather than the potential in using data-driven methods.

2.3. Systems engineering

Systems engineering is focused on the process of bringing human-made systems into being, beginning with the definition of need and extending through requirements analysis, functional analysis and allocation, design synthesis, design evaluation and system validation (Blanchard & Fabrycky, 1998). Systems engineering aims to ensure that human-made systems are properly coordinated and functioning with a minimum of undesirable side effects, such as costly and disruptive consequences. A large part of the focus of system engineering is to mitigate complexity and risk (Stevens, 1998). A system is a combination of elements or parts forming a uniform whole, and a system is composed of components, attributes and relationships between integrated parts. Systems engineering is a structured, multi-disciplinary engineering approach for the development of complex technical systems, targeting a cross-disciplinary optimum within a given time frame and budget.

Within systems engineering, design for reliability is one aspect. Reliability may be defined as the probability that a system or product will perform in a satisfactory manner for a given period when used under specified operating conditions. Blanchard and Fabrycky (1998) continue: “Reliability is one of the most important design parameters. Many systems today are highly sophisticated and will fulfil most expectations when operating. However, experience has indicated that these systems are inoperative much of the time, requiring extensive maintenance and expenditure of scarce support resources. In an environment of scarce resources, it is essential that reliability be considered a major system parameter during the design process”. Sherwin (2000) states that maintenance management has always been one step behind the development of production systems.

From the handbook of INCOSE (2020); the technical processes and how needs are transformed to requirements are described in Figure 9.

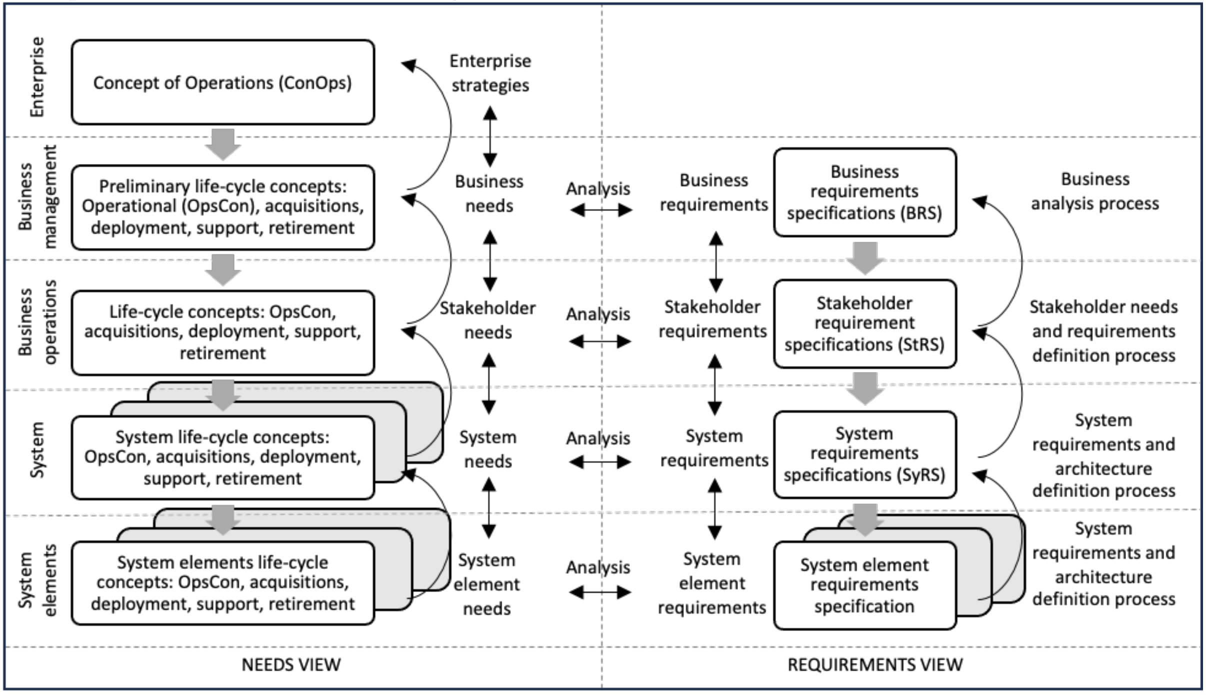


Figure 9: Transformation of needs into requirements. Adapted from INCOSE Handbook (2015).

2.3.1. Concept of Operations

The terms ConOps and OpsCon are used in slightly differing ways in literature, sometimes interchangeably. For the purposes of this study, ConOps refers to the intended function of an enterprise and OpsCon describes how a system works from the operator's perspective. The ConOps/OpsCon method was introduced by Fairley and Thayer (1997) as a bridge from operational requirements to technical specifications. The key task in the development of a ConOps/OpsCon is the allocation of functions and stakeholder requirements to elements of the proposed system on a high level. ConOps/OpsCon documents have been developed in many domains, such as the military, health care, traffic control, space exploration and financial services, as well as various industries such as nuclear power, pharmaceuticals and medicine, but is less established in production system design. The document is a user-oriented document that describes a system's operational characteristics from the end user's viewpoint. It is used to communicate overall quantitative and qualitative system characteristics among the main stakeholders. ConOps/OpsCon documents are typically based on textual descriptions, but may include informal graphics that aim to portray the key features of the proposed system, for example its objectives, operating processes and main system elements. ConOps/OpsCon can be considered as a transitional design artefact that plays a role in the requirements specification during the early stages of the design and involves various stakeholders (Kaasinen et al., 2022; Madni & Orellana, 2018). The authors rate the method as "a promising method and design tool that provides means to describe different actors and interdependencies between them. Compared to earlier methods based on modelling, it better supports both the dynamic nature of the overall system and co-design and development activities with relevant stakeholders". During the ConOps/OpsCon development process, each actor can be described in more detail and can be used in co-designing activities when defining, for example, the operator role in a new system. When completed, the ConOps/OpsCon can be presented with different levels of detail so that, by zooming in and out of the hierarchy, different elements of the system come into focus, and is a boundary object promoting communication and knowledge sharing (Kaasinen et al., 2022). It is worth noting that some companies perceive the development of ConOps/OpsCon as demanding and resource-intensive (Mostashari et al., 2012). The key characteristics are summarised as follows:

- Allocating functions and stakeholder requirements from high-level system to sub-systems
- Describing the system's operational characteristics in a user-oriented artefact
- Communicating overall quantitative and qualitative system characteristics among main stakeholders
- Describing each actor in detail to be understood to a fuller extent
- Presenting different levels to be able to zoom in and out of the hierarchy

2.3.2. Model-based Systems Engineering (MBSE)

Engineers have used models in a variety of forms for centuries, while "engineering with models" has been an integral part of the engineering profession for decades (Madni et al., 1990). The earliest published introduction of the concept of model-based system design can be found with Zeigler and Rosenblit (1988), and the concept was associated mainly with mathematical and computational models (Wymore, 1967) (Wymore, 2018). Estefan (2007) states that "MBSE methodology can be characterised as the collection of related processes, methods, and tools used to support the discipline of systems engineering in a 'model- based' or 'model-driven' context" and continues that MBSE is about "elevating models in the engineering process to a central and governing role in the specification, design, integration, validation, and operation of a system". According to Madnie & Sievers (2018) , early adoption of MBSE shows evidence of reduced development time and error rates. In part, this can be attributed to developing a better understanding of the problem.

Wynn and Clarkson (2024) mention the power of modelling and creating visual artefacts to generate insights for planning, execution and improvement of the design and development process. The increase in complexity of modern systems results from the number of system elements and the amount of information and knowledge needed to describe the system (Madni & Purohit, 2019). Systems Engineering is an approach to handle the increasing complexity and is frequently associated with document-based engineering (Estefan, 2007) (Berschik, 2023). A study in the case company by Hane Hagström et al. (2022) showed that production system engineers are using a total of 46 different document types for equipment acquisition projects alone, with none of them being model-based but in the form of drawings or tests. To overcome the challenges of document-based SE, MBSE shifts the focus to more formal modelling and the integration of different views into a consistent system model (Ramos et al., 2011) . In MBSE the approach is formalised to model information about system requirements, design, analysis verification and validation activities, and serves as a central repository for design decisions (INCOSE, 2020). Models are central to documenting results, applying simulations, analysing different solutions, and transferring knowledge in various engineering activities. When engineering modern systems involving services and subsystems from various engineering domains, different perspectives have to be addressed resulting in a heterogeneous model landscape (Kattner et al., 2019). To integrate the different perspectives and information, there is an increasing body of research focusing on MBSE (Berschik, 2023). Model-Driven Engineering focuses on the development of systems using models as a central part of the development process (Beydeda et al., 2005). To develop a system model, four elements are essential: the system model, a modelling method, a modelling language and a modelling tool (Delligatti, 2014) as seen in Figure 10.

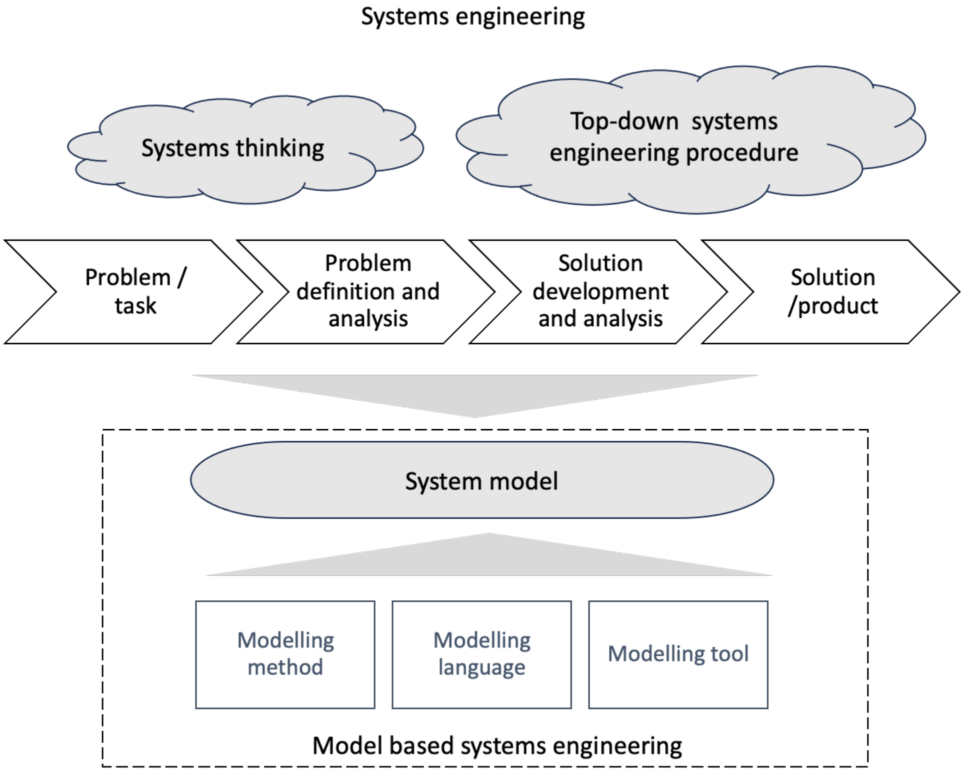


Figure 10: Elements to Model-Based Systems Engineering. Adapted from Delligatti (2014)

A literature review performed by Berschik et al. (2023) on the usage of MBSE in the engineering design community showed that of 56 papers selected for analysis, only three addressed the linkage between system and production. As systematic design methods are not that well implemented in production system design, this study aims to explore the potential benefits of using MBSE.

2.3.3. Human-centric systems engineering

Several researchers have addressed the need to extend the focus of the design of industrial systems to the whole sociotechnical system (e.g. (Amokrane-Ferka & Hein, 2022; Cagliano et al., 2019; El-Haouzi & Valette, 2021; Gräßler et al., 2021; Madni & Orellana, 2018; Neumann et al., 2021; Stern & Becker, 2019). They claim that human actors are often greatly simplified in model-based design, thus disregarding individual personality and skill profiles. Jones et al. (2018) identify the actors in Industry 5.0 manufacturing systems as human, organisational and technology-based agents. In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practices tend to address human considerations as an afterthought (Madni & Orellana, 2018). Madni et al. state the reasons as being a difference in terminology between human factor engineering community and traditional engineering, as well as shortcomings in presenting the value proposition of human system integration. In design of socio-technical systems, the technical, contextual and human factors viewpoints should be considered (Kaasinen et al., 2022). Human factors engineering is a scientific approach to the application of knowledge regarding human factors to the design of complex technical systems and can typically be divided into four groups: analysis, design, assessment and implementation/operation (Kaasinen et al., 2022). Kaasinen et al. states that one of the first tasks in the analysis step is to perform a Concept of Operations, a ConOps.

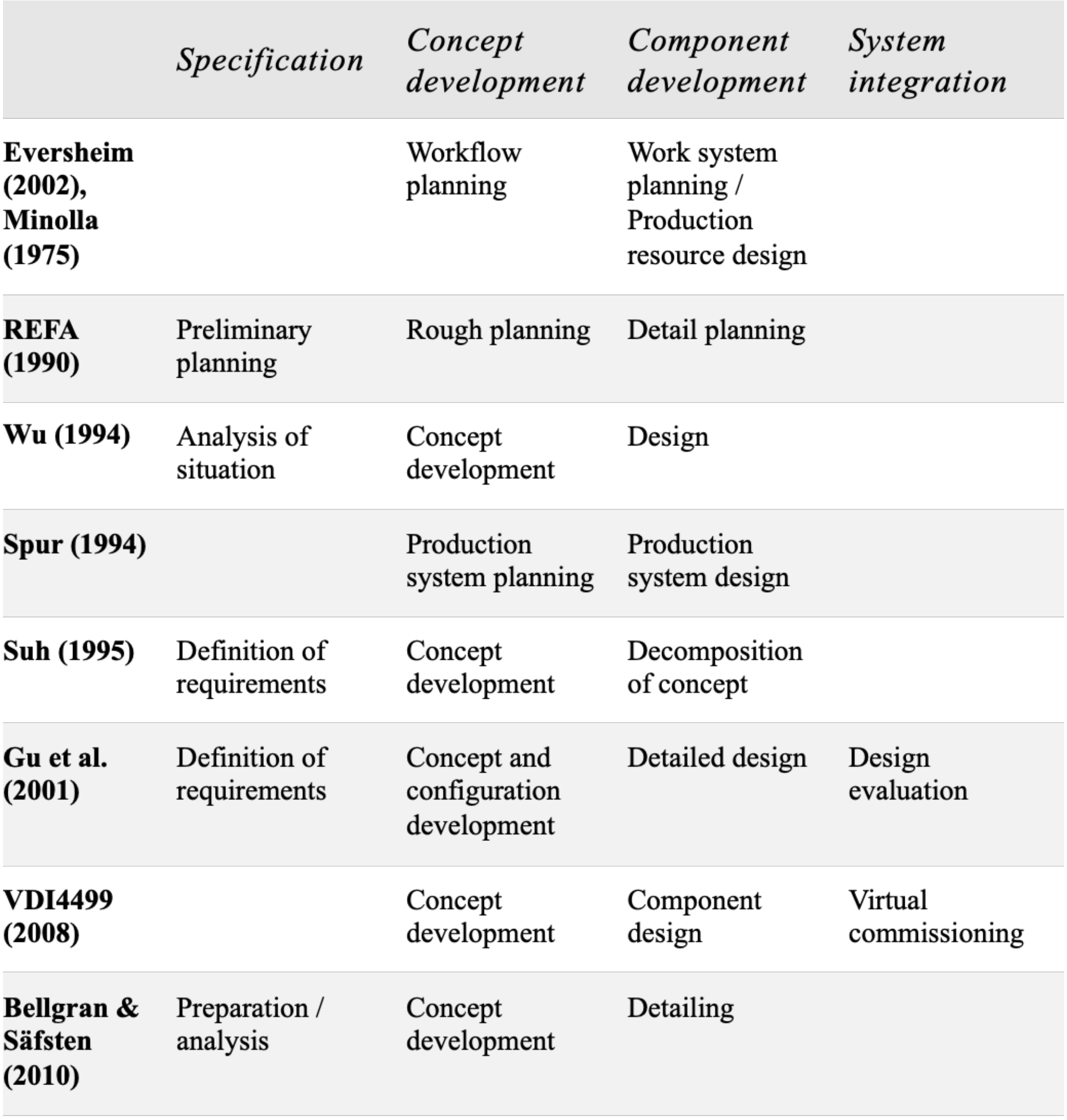
The objective of human-centred Model-based Systems Engineering is to incorporate human actions in multiple viewpoints (Madni & Orellana, 2018). Madni et al. state that a limitation of current Human System Integration (HSI) modelling tools is that they are independent of the architecture process and the decision-making in conceptual design of the system, and that no holistic approach for HSI exists. In today's systems engineering practice, the integration of humans into production systems is only pursued retrospectively, i.e. after the architectures have already been specified and designed (Gräßler et al., 2021). The authors continue: "Model-based development offers the potential to improve the integration of human needs into early system design". The human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk (Handley & Smillie, 2008), and should therefore be included and appropriately modelled (Madni & Orellana, 2018). The origin of Human Factors started in ergonomics, but is now increasingly transitioning into systems engineering language (Amokrane-Ferka & Hein, 2022). The human-centred design describes concepts to include workers with different skills, age, labour and education in productions (Gräßler et al., 2021). Due to new requirements within the Industry 5.0 scope, larger amounts of data and knowledge are required, which in turn results in new requirements, such as for more decision-making capabilities, more social interactions and a broader variety of skills (Hannola et al., 2017).

Human System Integration is "a technical and management process for integrating human considerations within and across all system elements; an essential enabler to systems engineering practice" (INCOSE, 2020). NASA's HIS Practitioner's Guide defines HIS as "an interdisciplinary science, craft and art to integrate humans, technical systems and organisations into efficient, safe and user-friendly systems" (Zumbado, 2015). According to Neumann and Du (2010), the careful consideration of the human being in the design can improve productivity, quality and technology implementation, and can have intangible benefits for operations while also improving worker well-being and working conditions. There is clearly a need to develop work allocation and teamwork in human-machine teams so that human workers feel they are in the loop and human jobs remain meaningful and manageable (Kaasinen et al., 2022). Workers' rights to varied and challenging work, good working conditions, learning opportunities, scope for decision-making, good training and supervision and advancement opportunities are in line with the initial value system in sociotechnical design, even though technology and organisational structures might change in industry (Mumford, 2000). Neglecting human factors can lead to performance degradation because the human and machine components of the production systems are not coordinated effectively (Gräßler et al., 2021).

2.4. Production systems design

Production is the transformation process whereby an input into a system is transformed into an output (Wu, 1994). It is a process of combining materials, resources, labour and capital in order to create products and/or services (Jonsson & Mattsson, 2009). A number of areas are required for the transformation: technology, people, energy and information need to be organised and managed in an effective way to make the transformation possible (Bellgran & Säfsten, 2005). The production system requires a holistic perspective and the sub-parts of the system with their internal relations contribute to realise the transformation. Facilities, people and equipment (e.g., machines), software and procedures are considered to be elements of the production system, which all have relations to each other (Löfgren, 1983). Whereas engineering design is traditionally seen from a physical product perspective, Pahl and Beitz (1996) state that "design tasks related to production machines, jigs and fixtures and inspections equipment (…) fulfilling the functional requirements and technological constraints are equally important". They also mention the importance of a systematic methodology being in place to ensure designers reach potential solutions quickly and directly, and for design methodology to foster and guide the abilities of designers, encourage creativity and at the same time focus on the need for objective evaluation of results. Systematic design aims to rationalise the design and production processes. The development of a production system follows the product development steps (Stoffels et al., 2021) with the main methods and authors described in Table 2, where ConOps and OpsCon are considered to belong to the concept development phase.

Table 2: Overview of established approaches and methodologies within the domain of production system development, based on Stoffels (2017)

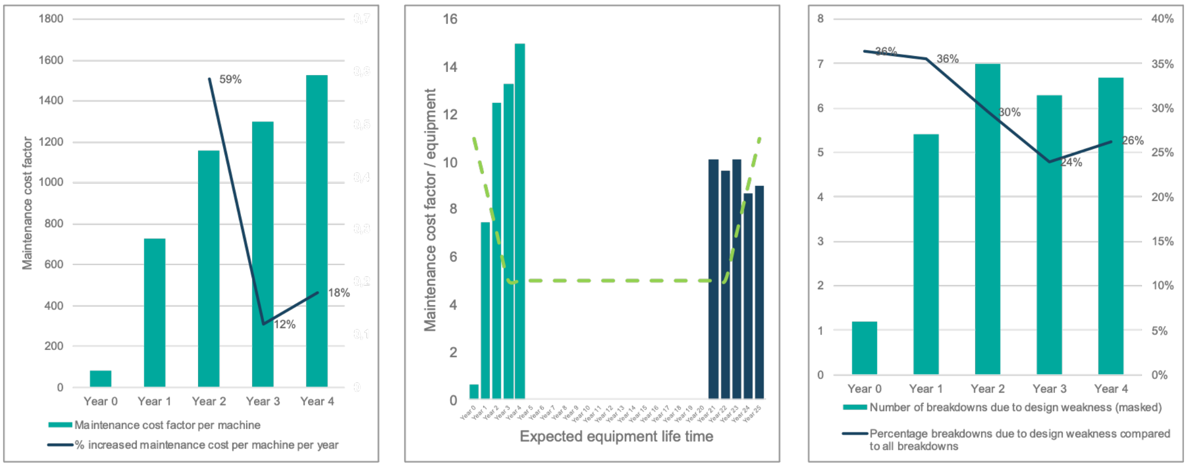


	Specification	*Concept development*	*Component development*	*System integration*
Eversheim (2002), Minolla (1975)		Workflow planning	Work system planning / Production resource design	
REFA (1990)	Preliminary planning	Rough planning	Detail planning	
Wu (1994)	Analysis of situation	Concept development	Design	
Spur (1994)		Production system planning	Production system design	
Suh (1995)	Definition of requirements	Concept development	Decomposition of concept	
Gu et al. (2001)	Definition of requirements	Concept and configuration development	Detailed design	Design evaluation
VDI4499 (2008)		Concept development	Component design	Virtual commissioning
Bellgran & Säfsten (2010)	Preparation / analysis	Concept development	Detailing	

Ulrich et al. (2020) state that one major challenge of the product development process is to transfer a tremendous amount of information and knowledge within and between development teams. Other challenges in traditional product development models typically lead to a number of problems commonly seen in companies, some of which are: (i) work overload of designers and engineers who frequently perform unnecessary tasks, (ii) models that are not clearly understood by designers, (iii) project cost overruns, (iv) difficulty in retrieving knowledge from previous projects and (v) ambiguity regarding tasks' responsibilities due to insufficient commitment of functional departments (Tortorella et al., 2016). Pahl and Beitz (1996) discuss design for production, the purpose of which is to design the product in a way that minimises production costs and times while maintaining the required quality of the product.

2.5. Production systems design capabilities

In previous studies, Hane Hagström has shown that there are challenges with industrial equipment acquisitions (Hagström et al., 2022; Hane Hagström, 2021; Hane Hagström et al., 2020). The studies show that when focusing on maintenance cost as one indicator of the production system design capabilities, maintenance costs grow in the early life of a machine, which is not the aim; that new equipment has higher maintenance costs than old machines nearing their end of life; and that design errors account for about 20-25% of the reasons behind unplanned machine downtime, see Figure 11.



Maintenance costs for the company increase in the early life of the new equipment

The new machines have higher maintenance costs than older machines

Design errors impact machine performance for several years

Figure 11: Summary of Hane Hagström et al. research regarding production system design capabilities (2020, 2021, 2022)

This data could mean that the production system design state of practice has potential for improvement. Hagström also showed that in the case company, industrial equipment acquisition currently largely takes place a) using traditional engineering methods of document-based stage gate models, b) that there is lack of external and academic influence, and c) that in the engineering community, the average working time in a company is 25.7 years, ranging from a minimum of seven years to a maximum of 44 years.

2.6. Cyber-physical production systems

As computer and information technology has evolved, a new engineering system, cyber-physical systems (CPS), has emerged, overlapping and integrating multiple fields of science and engineering (Liu et al., 2017). According to Liu et al., the present definitions of CPS are mostly given by different scholars from their own perspectives. E. A. Lee defines CPS as the integration of calculation and physical process, which involves embedded computer and networks monitoring and controlling the physical processes (Lee, 2007). Rajkumar (2010) defines cyber-physical production systems as “physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core”. Monostori defines CPS as “systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet (Monostori, 2014)”. Monostori continues: “Cyber-physical production systems consist of autonomous and cooperative elements and sub-systems that are getting into connection with each other in situation dependent ways, on and across all levels of production, from processes through machines up to production and logistics networks”.

Cyber-physical production systems are relevant for the work in this thesis as the production systems studied are physical production systems, manual, semi-automatic and fully automatic, which also exist in a digital landscape for monitoring and controlling.

2.6.1. Industry 4.0

The notion of Industry 4.0 was coined by (Kagermann et al., 2011) and fuses the virtual and the real world with emphasis on engineering applications such as robotics, digitisation and automatisation. For any system to be regarded as Industry 4.0, constant connectivity, human assistance and decentralised decision-making are absolute necessities. The essential components of Industry 4.0 comprised cyber–physical systems (CPSs), additive manufacturing, virtual and augmented reality, cloud computing, big data analytics, data science etc., to name a few. Industry 4.0 advanced the concept of Cyber Physical Systems into Cyber Physical Production Systems (Monostori et al., 2016), promoting the idea that the production system is a key enabler for Industry 4.0. A criticism of Industry 4.0 is that although many of the technologies have been available for a long time, for some reason they have not been implemented (Akundi et al., 2022; El-Haouzi & Valette, 2021). Industry 4.0 became largely understood to have the sole focus of improving process efficiency, thus ignoring the human costs of process optimisation and reducing focus on the principles of social fairness (Nahavandi, 2019) (Xu et al., 2021). At the same time, industry has seen a massive increase in environmental pollution, which was not strongly addressed in Industry 4.0 concepts (Nahavandi, 2019) (Xu et al., 2021). During this period, the Covid pandemic, the consequences of Brexit and the war in Ukraine drove industry to become more resilient to external situations. From these aspects, Industry 5.0 was launched by Michael Rada in 2018 (Rada, 2018) to focus societal sustainability, human well-being and resilient value creation. Since 2017, scattered academic efforts have been pushing the introduction of the Fifth Industrial Revolution (Xu et al., 2021).

2.6.2. Industry 5.0

Industry 5.0 is described as “the movement to bring the human touch back to the manufacturing industry” or to “leverage the unique creativity of human experts to collaborate with powerful, smart and accurate machinery” (Akundi et al., 2022). Governmental institutions are starting to explore the concept in several publications, for example the European Union (M. Breque et al., 2021). Industry 5.0 complements the techno-economic vision of the Industry 4.0 paradigm by emphasising the societal role of industry. It can enhance the quality of production by assigning repetitive and monotonous tasks to robots/machines and tasks requiring critical thinking to humans (Maddikunta et al., 2022), decrease emphasis on technology and assume that potential for progress is based on collaboration between humans and machines. Communication and employee motivation are boosted by interactive knowledge environments (Adel, 2022). Industry 5.0 is revolutionising manufacturing systems across the globe by taking away repetitive tasks from human workers.

Industry 5.0 recognises the power of industry to achieve societal goals beyond jobs and growth, and to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the wellbeing of the worker at the centre of the production process (Xu et al., 2021). The core values of Industry 5.0, as described by Maija Breque et al. (2021), are human-centric, resilience and sustainability. The enabling technologies, as described by Villani et al. (2020), are individualised human-machine interaction enabling technologies that combine the strength of humans and machines, bio-inspired technologies and smart recyclable materials, digital twins and simulation to model entire systems, data and analysis technologies that are able to handle data and system interoperability, and artificial intelligence to detect causalities and technologies for circularity. According to Villani (2020), these technologies support the value generation of Industry 5.0 in the form of profitability, scalability and business models, CO2 reduction and circular economy, and societal challenges and human-centricity. The values, enabling technologies and value generations are illustrated in Figure 12.

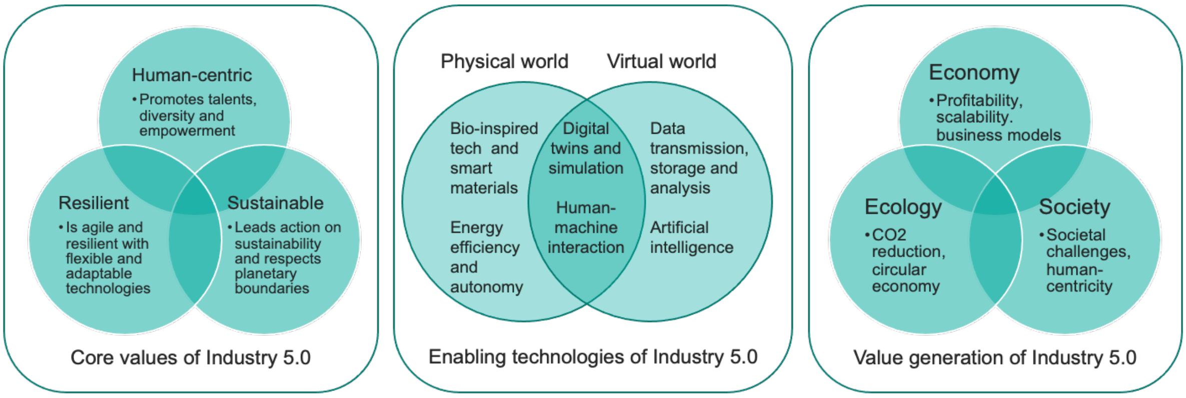


Figure 12: Industry 5.0 core values, enabling technologies and value generation, adapted from Breque et al. (2021), and Villani et al. (2020).

Xu et al. pose the question if we are living amidst a socio-technical revolution, meaning that the more human-centric Industry 5.0 and the more technology-centric revolution of Industry 4.0 are evolving together. The engineering in itself of industrial products, processes, and systems has long been recognised as a sociotechnical process (De Weck et al., 2011), where the successful delivery of manufactured products largely depends on the process by which they are designed and manufactured. Studies co-written by the author of this thesis have shown that the maturity in industry to understand the socio-technical aspects of its own work is limited (Eckert et al., 2020; Eckert et al., 2022). Manufacturing industries invest continuously in improving and renewing these processes. Mature businesses such as manufacturing in the automotive sector have for decades stayed competitive through a combination of economy of scale and continuous improvement along with offering more advanced products. Management approaches such as lean manufacturing (Womack et al., 2007) and Six Sigma (Schroeder et al., 2008) build on rational and data-driven prediction, analysis, and decision-making (Ustundag & Cevikcan, 2018). Manufacturing companies are often large, global, complex organisations where practices, norms and tools for the processing of data typically vary.

A bibliometric analysis of research in the field of industry 5.0 shows that the concept is still at a very nascent stage (Tunji-Olayeni et al., 2024). From the studies that exist, several disadvantages of Industry 5.0 have been identified. The limitations vary from a need to retrain workers in both technological and organisational skills (Narvaez Rojas et al., 2021) to a need for large investments in more sophisticated digital hardware and software (Tripathy & Pattanaik, 2020), which will create an environmental burden when abandoning obsolete equipment. Other concerns regard security and privacy for individuals as well as access control and audit possibilities (Maddikunta et al., 2022).

2.7. Frame of reference summary matched to research gaps

This section summarises the frame of reference chapter, highlighting the main references, main takeaways and the match to the identified research gaps.

2.7.1. Summary of Frame of Reference

The summary is documented in Table 3, presented chapter by chapter, the topic of the chapter, the main references for the chapter, the purpose of the topic, the main takeaways and the match to research gaps RG1 and RG2.

Table 3: Summary of Frame of Reference, presented chapter by chapter, the topic of the chapter, the main references for the chapter, the purpose of the topic, the main takeaways and

the match to research gaps RG1 and RG2.

Chapter	Topic	Main references	Purpose	Main takeaways	Match to research gaps
2.1	Product development	(Ulrich et al., 2020) (Pahl & Beitz, 1996) (G.L. Tortorella et al., 2016) (Isaksson & Eckert, 2020)	Framing the research context	Development is defining the physical form of the product to best meet customer needs, including engineering design (mechanical, electrical, and software) (Ulrich et al., 2020)	
2.1.1	*Design thinking*	(Cross, 1984) (Rowe, 1991) (Purdy & Popan, 2023) (Micheli et al., 2019)	Examining the method for prescriptive study	The major aspects of design thinking are understanding the practical and emotional needs of a client, using prototypes or physical models to explore possible ways of achieving goals (Purdy & Popan, 2023)	
2.2	Engineering design	(Cross, 1984) (Pahl & Beitz, 1996) (Chiarello et al., 2021)	Framing the research context	Design tasks related to production machines, jigs and fixtures and inspections equipment (…) fulfilling the functional requirements and technological constraints are equally important (Pahl & Beitz, 1996)	
2.3	Systems engineering	(Blanchard & Fabrycky, 1998) (Stevens, 1998) (INCOSE, 2015)	Framing the research context	Systems engineering aims to ensure that human-made systems are properly coordinated and functioning with a minimum of undesirable side effects, such as costly and disruptive consequences (Blanchard & Fabrycky, 1998)	
2.3.1	*Concept of Operations*	(Fairley & Thayer, 1997) (Madni & Orellana, 2018) (Kaasinen et al., 2022)	Examining the method for prescriptive study	Compared to earlier methods based on modelling, it better supports both the dynamic nature of the overall system and co-design and development activities with relevant stakeholders (Kaasinen et al., 2022) ConOps/OpsCon documents have been developed in many domains, such as the military, health care, traffic control, space exploration and financial services, as well as various industries such as nuclear power, pharmaceuticals and medicine, but to a lesser extent in production system design (author comment)	 RG1
2.3.2	*Model-Based Systems Engineering*	(Beydeda et al., 2005) (Madni & Purohit, 2019) (Berschik, 2023)	Examining the method for prescriptive study	To overcome the challenges of document-based SE, MBSE shifts the focus to more formal modelling and the integration of different views into a consistent system model A literature review performed by Berschik et al. (2023) on the usage of MBSE in the engineering design community showed that of 56 papers that were selected for analysis, only three of	 RG1

				them addressed the linkage of system and production (Berschik, 2023) A study in the case company by Hane Hagström et al. (2022) showed that production system engineers are using a total of 46 different document types only for equipment acquisition projects, with none of them being model-based but drawings or test	RG1
2.3.3	*Human centric systems engineering*	(Madni & Orellana, 2018) (Handley & Smillie, 2008) (Patrick Neumann & Dul, 2010)	Framing the research context + Examining the method for prescriptive study	The human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk (Handley & Smillie, 2008) According to Neumann and Du (2010), the careful consideration of the human being in the design can improve productivity, quality and technology implementation, and can have intangible benefits for operations while also improving worker well-being and working conditions. In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practises tend to address human considerations as an afterthought (Madni & Orellana, 2018)	RG2 RG2 RG2
2.4	Production systems design	(Pahl & Beitz, 1996) (Stoffels et al., 2021) (Bellgran & Säfsten, 2010) (Bellgran, 2003)	Framing the research context	The development of a production system follows the product development steps"(Stoffels et al., 2021) Designing a production system is a unique and complex task in which many parameters should be taken into account during the process of creating, evaluating and selecting the proper alternative. (Bellgran, 2003)	
2.5 + 1	Production systems design capabilities (including the introduction chapter)	(Islam et al., 2020) (Vielhaber & Stoffels, 2014) (Hane Hagström et al., 2022) (Arista et al., 2023) (Stark et al. 2017)	Framing the research context	There is still a lack of empirical studies on how or conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap (Islam et al., 2020). Vielhaber and Stoffels identified that in academia there is a larger focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts (Vielhaber & Stoffels, 2014). When focusing on maintenance cost as one indicator of the production system	RG1 RG1 RG1

				design capabilities, maintenance costs grow in the early life of a machine, which is not the aim; that new equipment has higher maintenance costs than old machines nearing their end of life; and that design errors account for about 20-25% of the reasons behind unplanned machine downtime (Hane Hagström et al., 2022) Only parts of the design process knowledge are captured explicitly using different documentation approaches and very little information persists from one design to another. Designers take decisions based on their assessment and experience (Arista et al., 2023) Today's manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity. In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity Stark et al. (2017)	RG1 RG1
2.6	Cyber-physical production systems	(Lee, 2007) Rajkumar (2010) (Monostori, 2014)	Framing the research context	CPS is the integration of calculation and physical process, which involves embedded computer and networks monitoring and controlling the physical processes (Lee, 2007).	
2.6.1	*Industry 4.0*	(Kagermann et al., 2011) (Monostori et al., 2016),	Framing the research context	Industry 4.0 advanced the concept of Cyber Physical Systems into Cyber Physical Production Systems (Monostori et al., 2016)	
2.6.2	*Industry 5.0*	(Akundi et al., 2022) (M. Breque et al., 2021). (Tunji-Olayeni et al., 2024).	Framing the research context	A bibliometric analysis of research in the field of industry 5.0 shows that the concept is still at a very nascent stage (Tunji-Olayeni et al., 2024).	

2.7.2. *Summary of challenges in the product development process in general*

Ulrich et al. (2020) state that one major challenge of the product development process is to transfer a tremendous amount of information and knowledge within and between development teams. Other challenges in traditional product development models usually lead to a number of problems commonly seen in companies, some of which are: (i) work overload of designers and engineers who frequently perform unnecessary tasks, (ii) models that are not clearly understood by designers, (iii) project cost overruns, (iv) difficulty in retrieving knowledge from previous projects and (v) ambiguity regarding tasks' responsibilities due to insufficient commitment of functional departments (Tortorella et al., 2016). General challenges with the product development process are described in Figure 13.

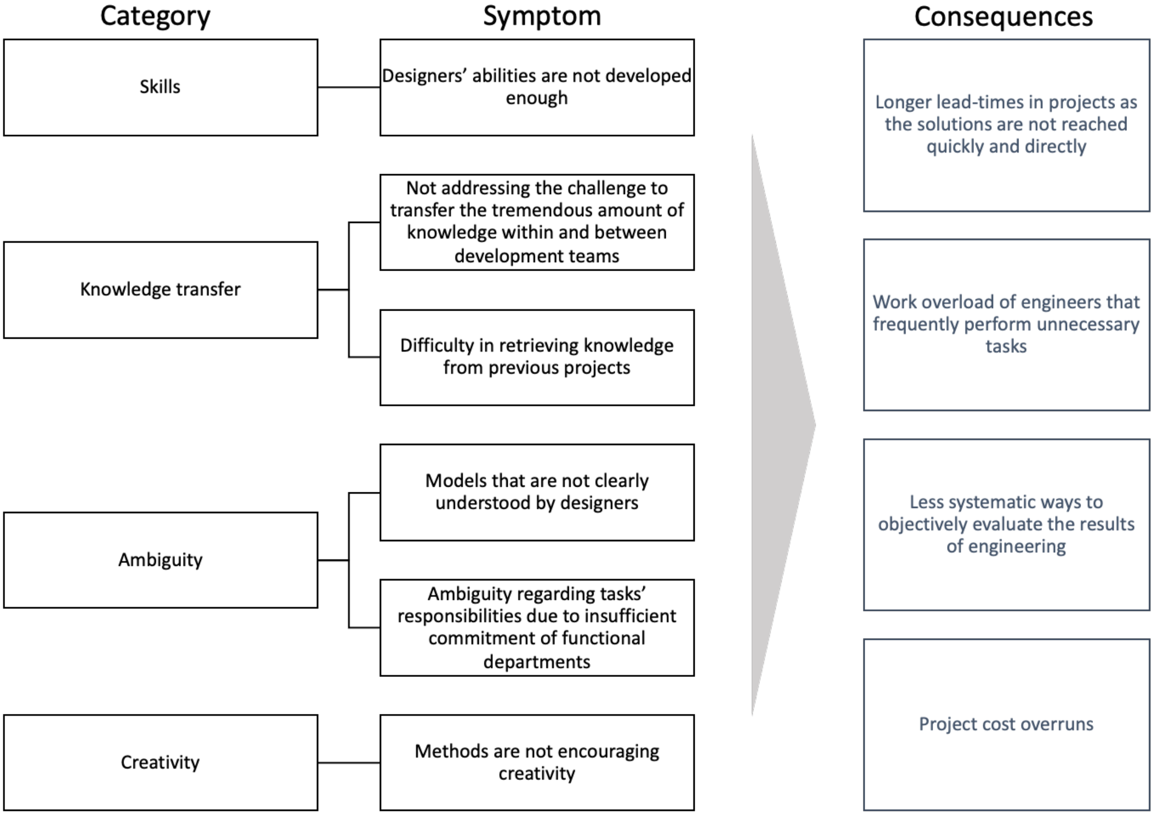


Figure 13: General challenges with the product development process in category, symptom and consequences (Ulrich et al., 2020) (G.L. Tortorella et al., 2016)

2.7.3. Summary of Research Gap 1

Research gap 1 (RG1): Lack of systematic and effective systems engineering design methods in production system design.

- Methodologies and process models dedicated to production development have lower scientific coverage than their product-oriented counterparts (Vielhaber & Stoffels, 2014) (Islam et al., 2020)
- Common practice that production system designers take decisions based on their assessment and experience rather than true systems engineering design (Arista et al., 2023) (Stark et al., 2017)
- Only parts of the design process knowledge are captured explicitly using different documentation approaches and very little information persists from one design to another (Arista et al., 2023)
- There is limited usage of Model-based Systems Engineering in production system design (Berschik, 2023)
- Production system engineers mainly use text documents or drawings for equipment acquisition projects, with less use being made of models or Model-based Systems Engineering (Hane Hagström et al., 2022)
- Production equipment losses due to production system design weaknesses is increasing (Hagström et al., 2020)

2.7.4. Summary of Research Gap 2

Research gap 2 (RG2): Lack of inclusion of human aspects in the production system design. The main weaknesses identified in literature are:

- A failure to address the human in the system, as the human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk (Handley & Smillie, 2008)
- Not considering the human being in the design can impact productivity, quality and technology implementation as well as worker well-being and working conditions (Patrick Neumann & Dul, 2010)
- In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practices tend to address human considerations as an afterthought (Madni & Orellana, 2018)

3. Research approach

This chapter presents the research approach used to answer the research questions. The research methodology with validation and verification of design research is elaborated on. The applied research approach and the case company are described.

3.1. Research methodology

Several authors have discussed the need for design research to be scientific (Blessing and Chakrabarti (2009)) and how to achieve a sufficiently scientific level in this type of research. Research in the engineering design field is not only understood as a pursuit of scientific knowledge; it also pursues the goal of practically improving engineering design and practice (Eckert et al., 2003). Ullman (2003) states that an estimated 85% of product development projects encounter problems in cost, time management or by simply not functioning as intended, which means the design process is worth studying to identify improvement areas.

To counter the critique of the scientific qualities of engineering design research, several researchers have suggested research approaches to guide researchers in the field. Among the most common methodologies applied is the Design Research Methodology (DRM) presented by Blessing and Chakrabati (2009a), which the work presented in this thesis has applied as described in Figure 14.

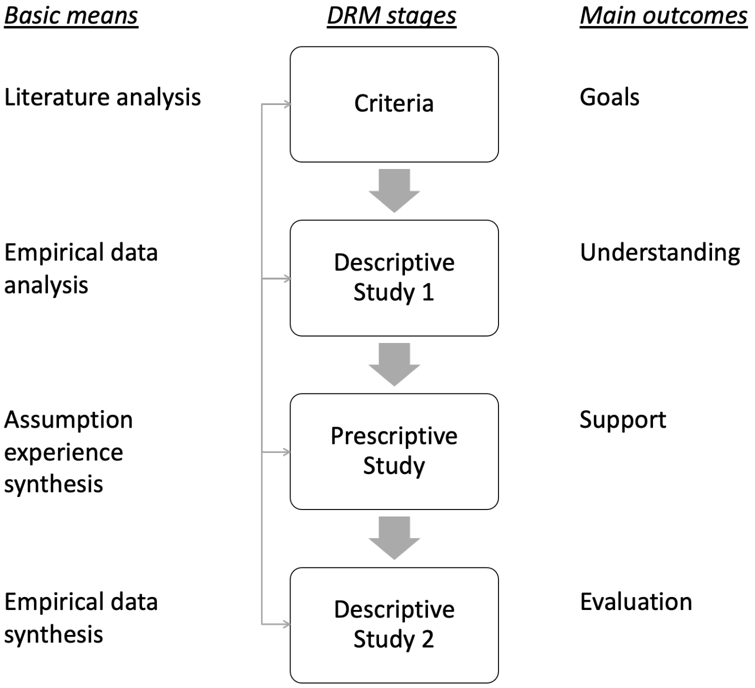


Figure 14: The DRM framework, from Blessing and Blessing and Chakrabati (2009a).

The DRM by Blessing and Chakrabarti (2009) is divided into four research stages: research clarification, descriptive study I, prescriptive study and descriptive study II. The work presented in this thesis focuses on the DS1 and PS. To be able to answer the research questions, literature studies supported by prescriptive case studies were selected as a research approach. The case studies included both qualitative and quantitative research methods.

3.2. Validation and verification of design research

In the validation of design research, the common themes to address are validation and verification (Isaksson et al., 2020). As Isaksson et al. (2020) state: *"How engineering design research can be validated in practice depends on the nature of the research that is being validated*". This is associated with two fundamental questions: *"Did we do the right things?"* refers to the validity of the research findings, while "*Did we do the things right?* Refers to the reliability of the research process. Validity intends to increase confidence in the ability of the research outcomes to describe the measured phenomena, and by verification the trustworthiness of the research outcomes can be increased (Creswell & Creswell, 2018). Le Dain et al. (2013) propose validation criteria as seen in Table 4, with empirical research validation criteria:

Table 4: Validity criteria according to Le Dain et al. (2013)

Dimension	**Empirical research**
Truth value	Credibility
Applicability	Transferability
	Analytical generalisation
Neutrality	Confirmability

Buur (1990) suggests that the quality of research can be confirmed by verification by acceptance, which aims to validate theories, methods or methodologies through their acceptance by other designers. Almefelt (2005) suggests using transferability to claim validity by the degree of generalisation beyond the research setting. According to Almefelt (2005), a careful description of the conducted research with regard to its context, hypothesis, sample and so forth can increase the degree of transferability. A major aim of engineering design research is to improve the practice of design. Thus, design research outcomes often regard design methods, methodologies and approaches to facilitate the practice of design. Complying with this aim, Seepersad (2006) describes research validation as "a process of building confidence in its usefulness with respect to a purpose," where "its" refers to the proposed design method. Pedersen et al. presented a prescriptive and systematic approach to validate and verify a design method (or "support" which is the term used by Blessing and Chakrabarti (2009)), called the validation square (Pedersen, Emblemsvag, et al., 2000), presented in Figure 15.

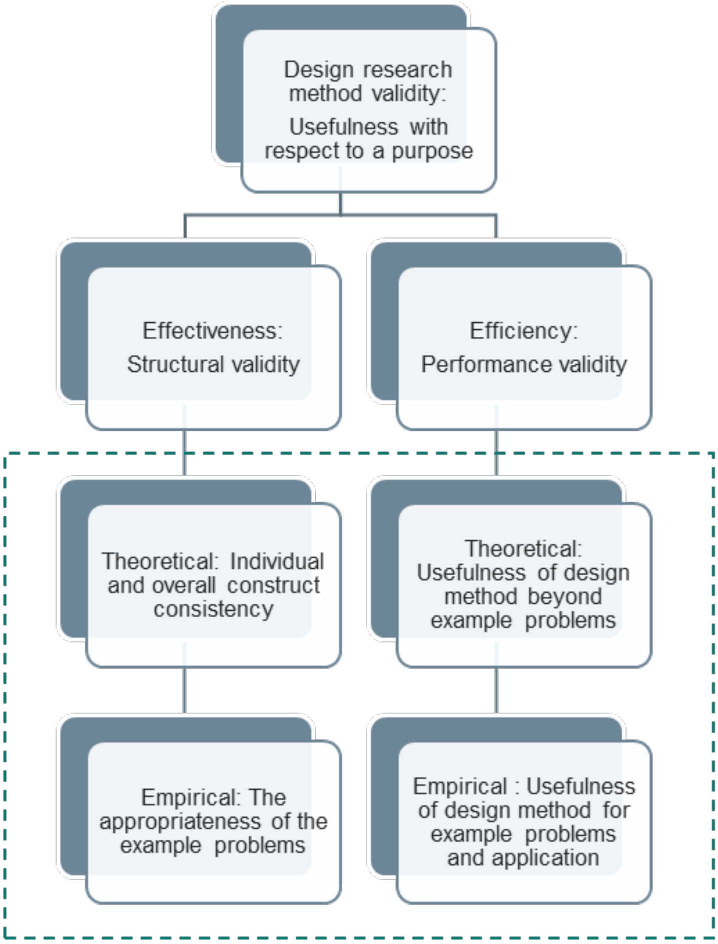


Figure 15: The validation square redrawn from Seepersad et al. (2006) and (Pedersen, Emblemsvag, et al., 2000)

The validation square, which is based on the works by Pedersen et al. (2000) incorporates the elements of evaluation suggested by Blessing and Chakrabarti (2009) and can be viewed as a complement to the DRM framework. To justifiably claim to have produced knowledge, as well as having improved an engineering design practice, the researcher needs to answer the question: "Are you doing the right research?" (Le Dain et al., 2013). This includes whether the research solves a problem, whether this problem actually exists, and whether it is relevant to the field of research. But beyond the validity of the research topic and questions, the proposed solution also needs to be valid, that is, it needs to be "useful[..] in respect to a purpose" (Barlas & Carpenter, 1990).

- Validation: Activities conducted to ensure that the resulting products meet the requirements for the specified application or intended use (customer needs)
- Verification: Activities conducted to ensure that the design output meets the input requirements (functional requirements and specifications)

Following these definitions, a research claim has to be validated, and the method supporting it has to be verified. Since engineering design research aims to contribute to two different goals, the research also has to be subject to two types of validation: while the academic results need to be valid in terms of methodical data collection and evaluation, the industrial side requires the methods and tools that are developed to be powerful, reliable and validated (Eckert et al., 2003). This is illustrated in the "Journey to Validation" by Isaksson et al. (2020) shown in Figure 16.

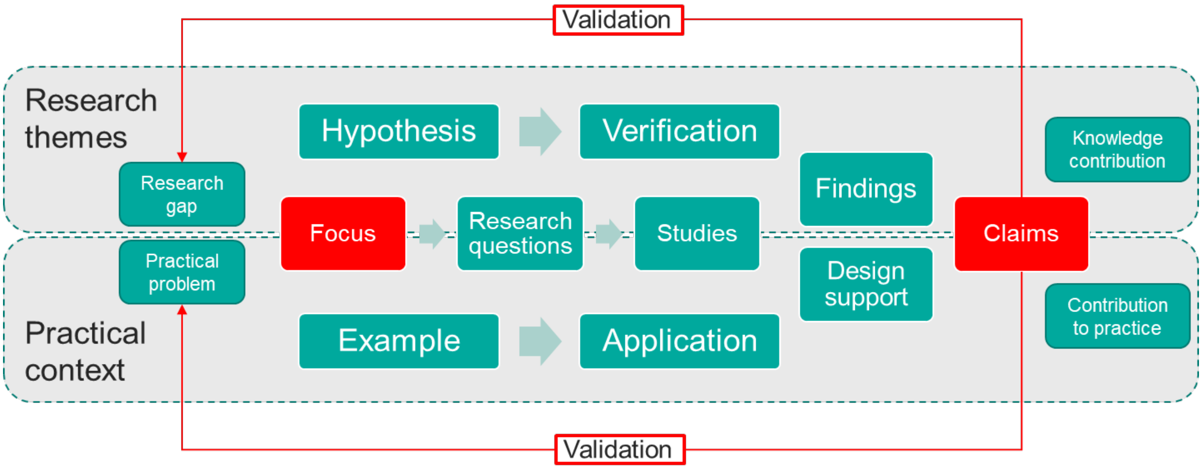
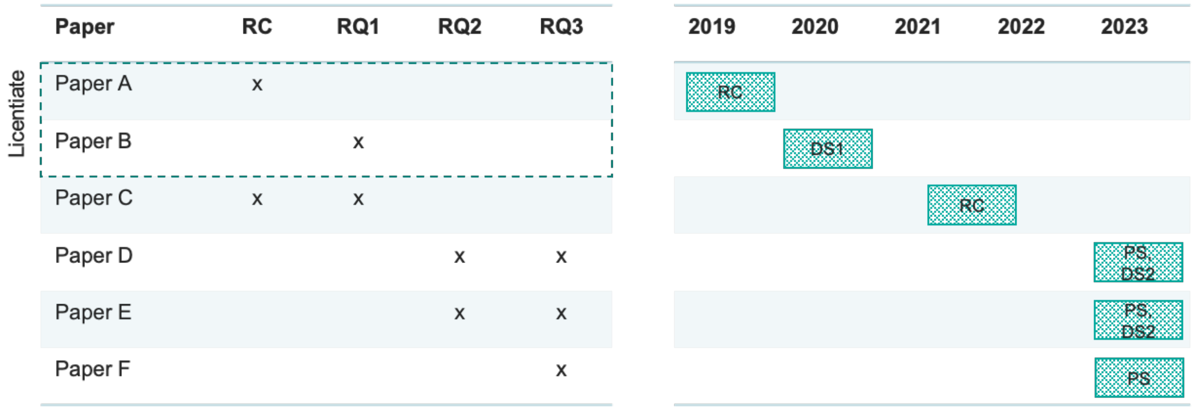


Figure 16: Journey to engineering design research validation, adapted from Isaksson et al. (2020)

In the work presented in this thesis, credibility is validated through confirmation with experts in the company, as well as confirmation in literature. Transferability is more uncertain; all studies except one were performed in a single organisation, albeit exploring several plants, projects and functions. Even so, findings may not be transferrable to other contexts.

3.3. Applied research approach for the work presented in this thesis

The studies have been designed to answer the research questions as described in Figure 17, with RC referring to Research clarification, PS (referring to Prescriptive Study) and DS2 (referring to Descriptive II).



Paper	RC	RQ1	RQ2	RQ3	2019	2020	2021	2022	2023
Paper A	x				RC				
Paper B		x				DS1			
Paper C	x	x					RC		
Paper D			x	x					PS, DS2
Paper E			x	x					PS, DS2
Paper F				x					PS

Figure 17: Paper contribution and timeline per RQ according to Design Review Methodology from Blessing and Chakrabarti (2009).

3.4. The case company

The case company is a global actor in the transport solution industry with about 100,000 employees worldwide. Several brands are represented in the portfolio as well as a variety of vehicles, from excavators to buses and trucks. The company is set up by several organisations who all interact on an operational level and the company has factories in 18 countries. In addition to its production sites, its global industrial operations include several product development centres and several parts distribution and logistics centres. Furthermore, there are assembly plants operated by independent companies at ten locations around the world.

The case studies were performed on two projects to set up new production lines for electric powertrain products using production processes previously unknown to the engineering departments. For both projects, the project goals were to create a human-centric production system, and the engineering goals were to manage risk, to manage complexity and to implement Industry 5.0. Based on the work from Chakrabarti (2003) which is discussed in Chapter 2, novelty is defined in relation to the knowledge base available. Ranging the levels of novelty starting from original design to novel design and finally disruptive design, the work presented in this thesis focus is on novel products and production systems. The battery products introduce fresh features and functionalities but does perhaps not upend existing norms or create entirely new markets.

The plan is to establish a battery cell production plant about 40 km from the battery assembly plant. The production management of the battery assembly industrial plant project was studied during 18 months, and at the start of the study the time plan was production within three years. The battery assembly plant is located within the compound of the already existing production facility of combustion engines, with the ability to take advantage of the vast and highly established industrial set-up. The battery assembly plant will distribute the batteries to the truck plants in the industrial system of the case company. The industrial flow is described in Figure 18, with the focus of this study circled for Paper D and E.

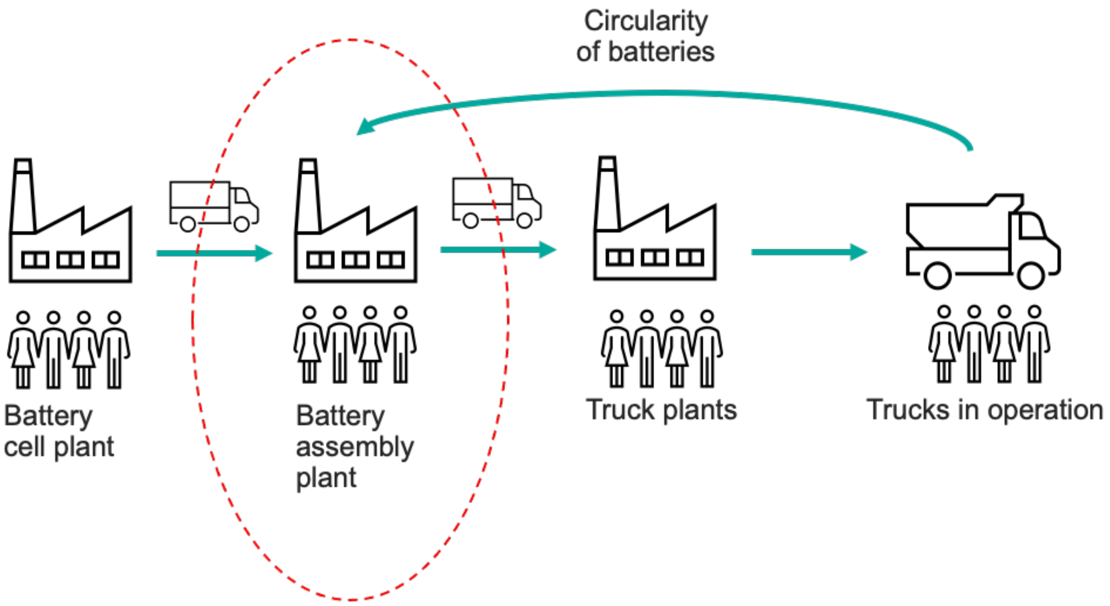


Figure 18: The planned industrial flow in the battery production system project with the focus of this study circled.

The battery cell plant was studied as well. The battery cell project was still in the concept phase and planning for production within five years. For Paper F the focus is described in Figure 19.

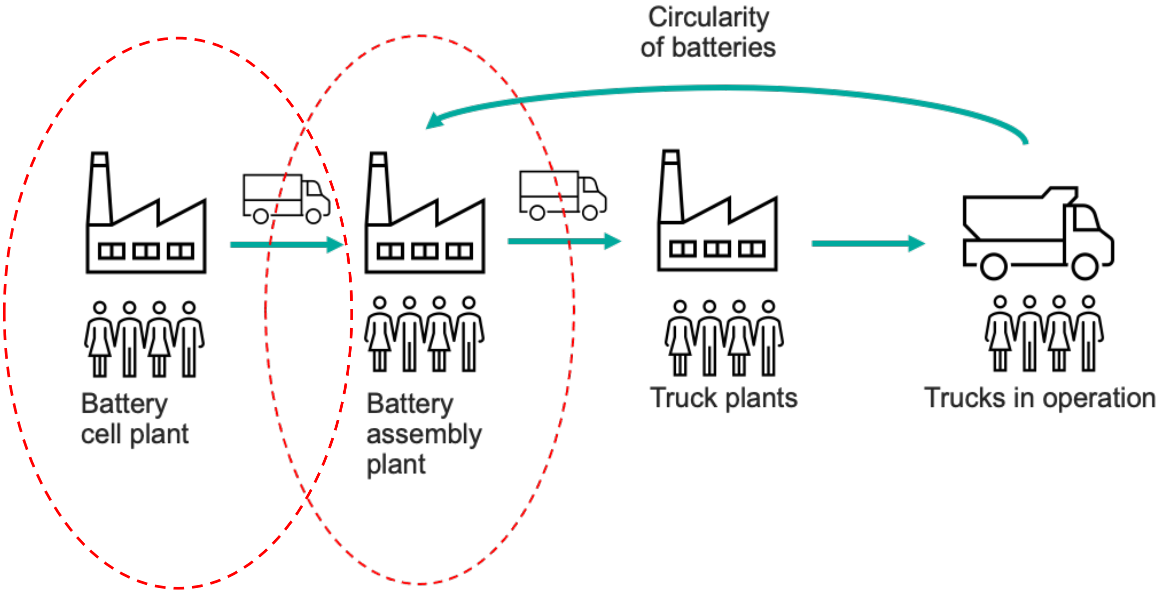


Figure 19: The planned industrial flow in the battery production system project with the focus of this study circled

The project aim is to set up a production system for battery assembly and distribution, including circularity flow of used batteries with remanufacturing of these.

3.5. Research approach - Paper A

For Paper A, the purpose was to understand which the main problems are in an end-to-end production process. A retrospective longitudinal case study using field data was designed for a representative flow in the heavy automotive industry. The flow selected is a high-volume flow, involving three main plants which are all located in Europe. Figure 20 shows the value flow in the study.

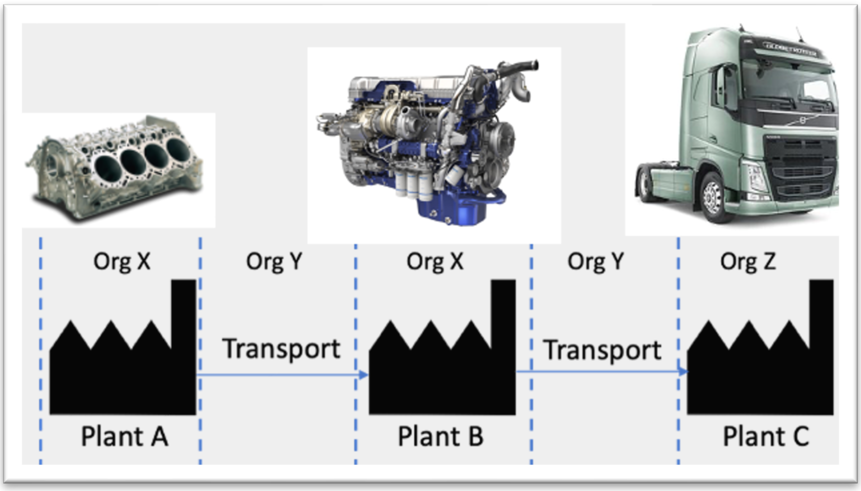


Figure 20: Visualisation of the value flow in the study (copyright Volvo Group)

The selected case study covers the life cycle from raw metal to finished truck, which means that the case study does not only study a limited part of the production flow. For the case study, a statistical method of inductive, comparative analysis is selected to answer the straightforward question: which loss is the largest? The academic value of this calculation is that the method of calculation is normally not performed in an entire flow, but only in one plant, and this means that new statistical models have to be used. A nominal factor also needed to be developed to be able to compare costs. The concept is to use the types of industrial losses that production flows have. To be able to quantify the impact of the losses, the attribute is the cost of the defined losses. The variables within the attribute are defined as 110 specific loss types which are each of the types of ratio and dependent variables. The characteristics of the data is raw data, field data, financial, empirical, objective, quantitative and secondary. The data is captured by the financial departments in the plants and reported in the financial systems in the company. The case company uses a method called cost deployment to quantify and visualise the main wastes and losses. This method has mainly been used within the perimeter of a plant, and this study tests this method on an entire flow between plants, from metal to finished truck. The research design is to use a case study from Volvo Group Operations by following a product from its start as metal scrap. This is cast, then machined, then sent to assembly to become an engine and then sent to a truck plant to become a truck. The research method is to collect already existing quantitative waste and loss data for one quarter (Q1 2018). The data represents the cost the company has borne for the loss, broken down to detailed level by much one extra step costs, how much one machine breakdown costs, etc. This data is consolidated each quarter, and one quarter equals close to 100,000 data points. The data is largely collected automatically, but also manually in the operating processes. The data is analysed through the use of quantitative and inductive statistics with comparative analysis.

3.6. Research approach – Paper B

For Paper B a qualitative study was designed focusing on how professional maintenance losses in production are addressed through efficient knowledge management in equipment acquisitions. This retrospective longitudinal and epidemiological case study was a field study based on interviews. This study investigates the industrial system engineering design from this perspective. Four cases were studied where the organisation already had one machine and bought another machine of the same type, see Figure 21.

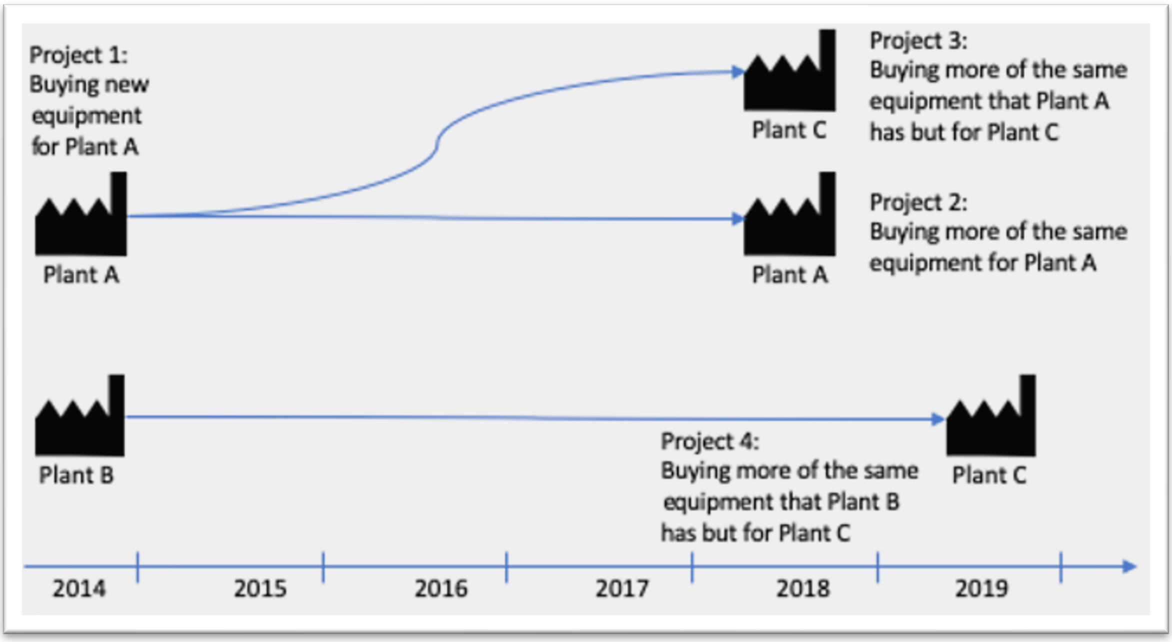


Figure 21: The four studied projects where the same type of equipment was purchased again

In theory, the knowledge of the problems in the machine should affect the buying of the new machine to ensure the same problems do not occur again. The barriers to capturing and transferring maintenance-related knowledge from operations into the process of procuring new equipment from suppliers were investigated. Literature studies were performed in the topics of lean thinking, maintenance, knowledge management and early equipment management. Case studies with interviews were performed, where the reliability of the data is enhanced by using a pre-set interview guide. Each interview is performed in pairs, recorded, transcribed and then reviewed by a third person. The validity is enhanced by using senior experts in the business to secure the relevance. To strengthen both validity and reliability, triangulation is used (qualitative data, review of internal documents and review of literature). The concept used for this study was the concept of maintenance knowledge in the acquisition process, with the attributes of knowledge capture, knowledge sharing and knowledge re-use. The variables are the 28 barriers for knowledge management (Riege, 2005) with individual, organisational and technological aspects, as well as the framework of activity theory (Engeström, 2000) for organisational learning, with the variables of instruments, subjects, rules, community division of labour, object and outcome. For both attributes, the variables are nominal and the type of data is primary, subjective, analytical, qualitative and experimental. Phenomenology was selected as the analysis method for this specific study, as the purpose was to capture the human experience of the process and capture the essence of what all the interviewees stated. The analysis methods selected were qualitative and phenomenological.

3.7. Research approach – Paper C

In the work presented in this thesis, several literature studies were performed during the research process. Search terms that were considered relevant and included in the literature reviews were “project management”, “communication”, “project communication”, “stage-gate”, “lean product development”, “agile product development”, “visualisation”, “visual planning”, “digital visual planning”, “change management” and “resistance to change”.

During the literature reviews, the searches were limited to the titles, abstracts and keywords of the literature. In addition, the documents included in the searches were restricted to articles, books, book chapters and conference proceedings. The reason for this was both to limit the amount of material to be assessed, and to ensure that the literature included was of adequate quality. The scientific publishing database Scopus was used to search for literature. The method of reviewing the literature varied throughout the process. In addition to searches in Scopus, the snowballing method was used. When applied to a literature review, snowballing is described by Bell et al. (2019) as the act of studying the references of relevant literature. This is known as backward snowballing. Another type of snowballing, which is conducted by studying literature that cites relevant literature, is referred to as forward snowballing (Wohlin et al., 2020). By doing this type of review, additional literature that was not found in the searches could be identified.

The most significant literature review was performed in Paper C. For this literature study, the systematic review approach was selected. As stated by Petticrew and Roberts (2006), a systematic review reduces the bias often inherent in traditional reviews and minimises the risk of missing out important literature. Another benefit of the systematic review is that the methodology can be described in detail, which means that the study can be more transparent than a traditional review (Snyder, 2019). As a result of the greater transparency, the ability to reproduce the findings is increased. Three databases were used: Scopus, Web of Science and Access Science. The keywords were combined into search strings with Boolean operators, together with a summary of the number of records that each search string produced. The search was limited to the title, abstract and keywords of the records, as shown in Table 5.

Table 5: Search strings for literature review with a summary of the number of records in the results.

Search strings:	**Number of hits:**
Barriers AND (“Industry 4.0” OR digitalisation)	812
(“Industry 4.0” OR digitalisation) AND (sociotechnical OR socio-technical)	222
(“Industry 4.0” OR digitalisation) AND (sociotechnical OR socio-technical) AND barriers	3
(“Industry 4.0” OR digitalisation) AND (engineer)	1004
“Engineer 4.0”	10
(“Industry 4.0” OR digitalisation) AND (“design management”)	20

Since the same search strings were used in more than one database, duplicates occurred in the searches in the different databases. To remove these duplicates and facilitate the screening process, all the results lists were imported into EndNote. After the duplicates had been deleted, the papers were screened by reading the title, abstract and keywords. If the titles were considered irrelevant at this stage, the papers were excluded. Where the titles were relevant, the abstract and keywords were read and added to the list of papers to be read in full. The main criterion for exclusion and inclusion was a connection to manufacturing industry or engineering. In addition, only published articles, conference papers, books and book chapters were included, and another criterion was a clear link to the research questions. An important note is that the latter criterion involves a risk of bias in terms of subjectivity, since it relies on the researcher’s interpretation of whether or not a paper is connected to the research question. In addition, this screening process was performed by one researcher only and no criteria relating to the type of paper were applied when screening, only the type of document as described. Few papers were identified that addressed the digitalisation effect of engineering. This fact indicates a potential gap in the research on the topic, which Hallstedt et al. (2020) have also identified. In order to find more papers on this topic, searches were carried out in other databases and snowballing was used. Snowballing is a method in which the reference lists of relevant papers are scrutinised with the goal of finding additional papers to include in the review (Hiebl, 2021). This approach enabled additional papers to be found, but as mentioned by Hiebl (2021), the transparency of the literature review is decreased since it is less structured and explicit. Furthermore, snowballing is a backward search, meaning that only older studies are found. The process of reviewing the existing literature is summarised in Figure 22.

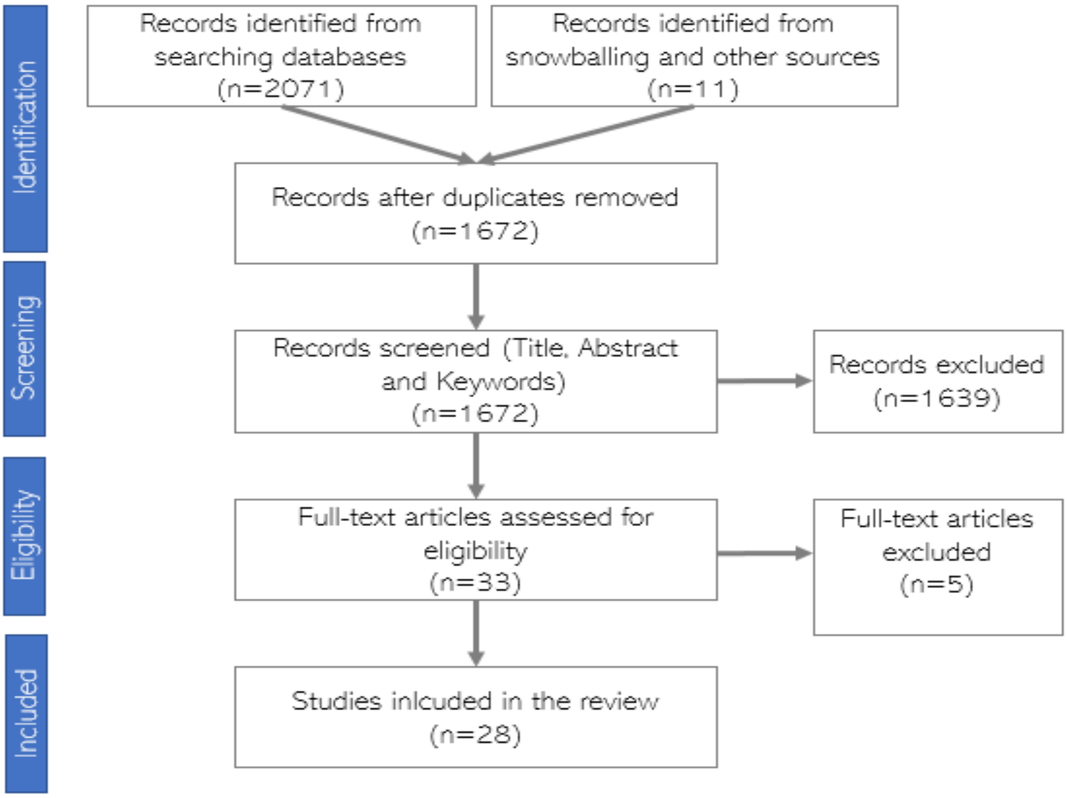


Figure 22: Literature review process including the number of papers found at each step

Twenty-eight papers were considered relevant and of sufficient quality for further analysis. These papers were analysed qualitatively and quantitatively in the NVivo software package. The papers were imported into NVivo and read in full. Coding was used to structure the information from the papers. Each barrier that was identified was assigned a code, which was used in the analysis so that barriers with the same meaning but different phrasing were grouped together. In addition, themes were identified, barriers that were connected were assigned a theme and the frequency of mentions was counted. The information from the papers was synthesised to provide a summary of the meaning of digitalisation and Industry 4.0 in the introduction section. To visualise the areas of relevance and contribution (ARC), a diagram of the research area was created based on the layout proposed by Blessing and Chakrabati (2009b) in Figure 23.

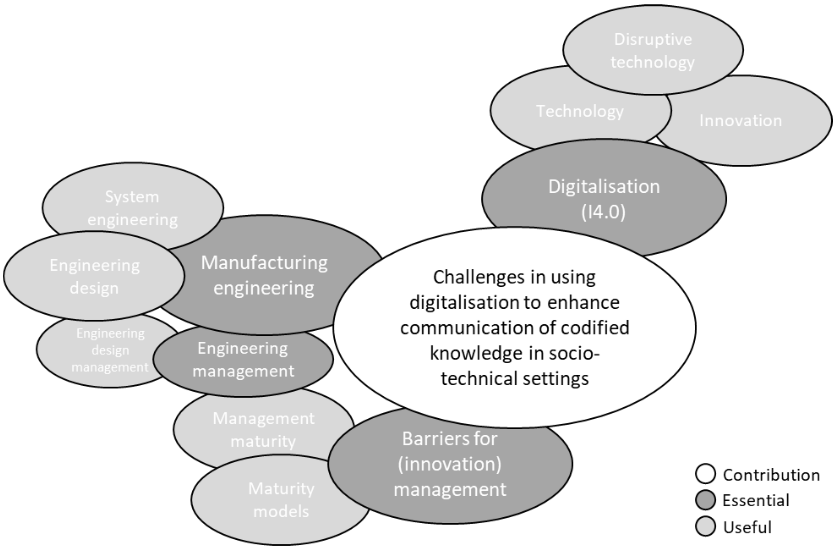


Figure 23: ARC diagram of research topics with the categories: most significant direct contribution, essential to the research context and useful for orientation purposes.

3.8. Research approach - Paper D

Paper D comprises a literature review and a comprehensive predictive study.

3.8.1. Literature review

For this paper, Figure 24 shows the topics considered relevant areas for research contribution in systems engineering.

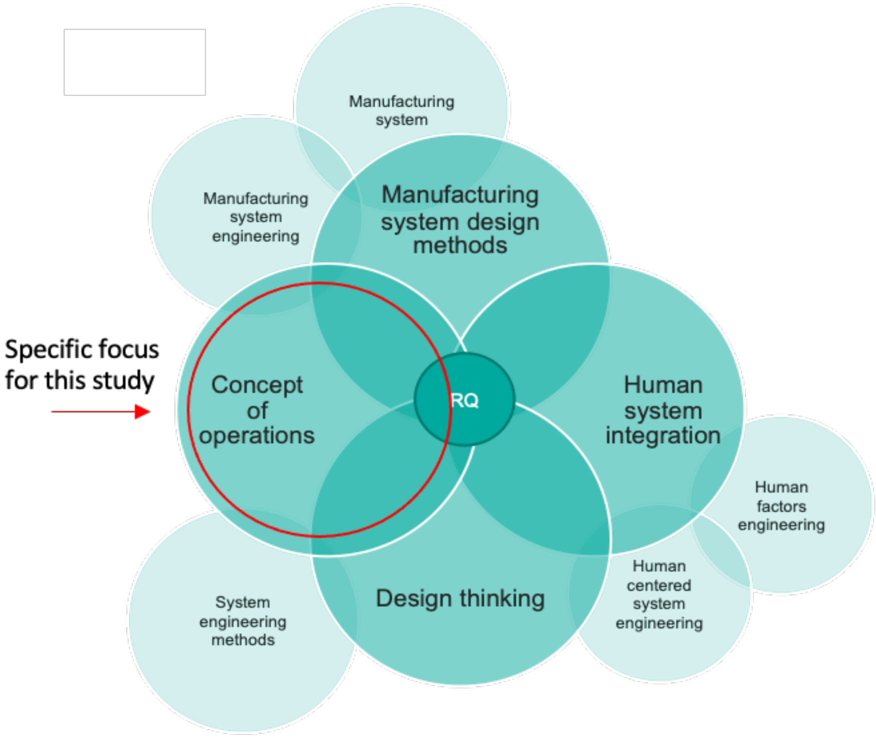


Figure 24: Areas for research contribution

A literature study was performed during the research process. The method of reviewing the literature varied throughout the process. Three databases were used: Scopus, Web of Science and Access Science, complemented by Google Scholar. The keywords were combined into search strings with Boolean operators, along with a summary of the number of records produced by each search string, with results limited to peer-reviewed full text and the scope of the years 2015-2023. Snowballing was used in several instances. The search was limited to the title, abstract and keywords of the records, as shown in Figure 7. Finally, a selection of 32 articles were considered relevant to reflect the ARC diagram in Figure 25.

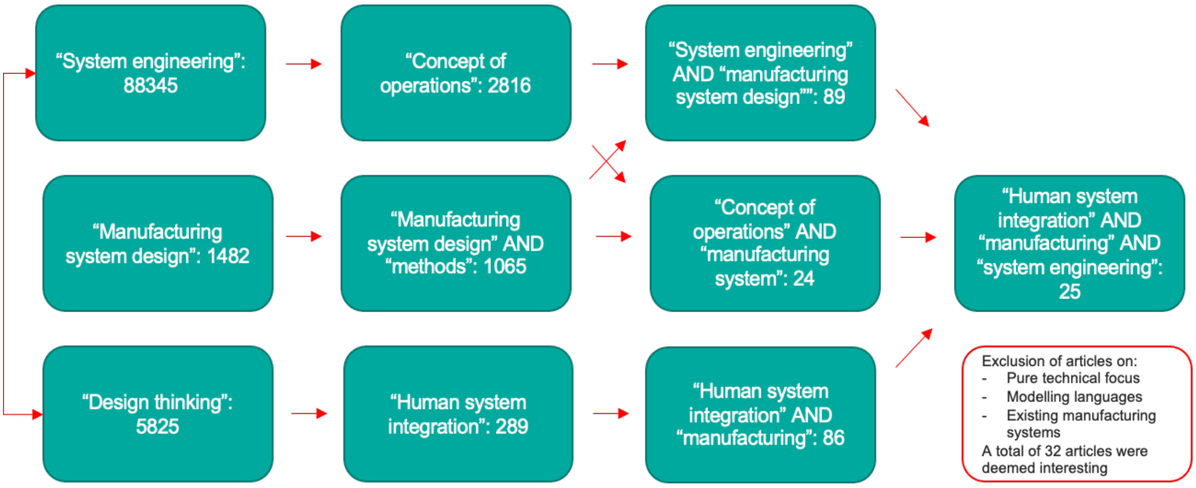


Figure 25: Search strings for literature review with a summary of the number of records in the results and a summary on how the 32 relevant articles were identified.

Since the same search strings were used in more than one database, duplicates occurred in the searches in the different databases. Where the titles were relevant, the abstract and keywords were read and added to the list of papers to be read in full. The main criterion for exclusion and inclusion was a connection to manufacturing industry or engineering. Articles focusing on pure technology, modelling languages and existing manufacturing systems were excluded. In addition, only published articles, conference papers, books and book chapters were included, and another criterion was a clear link to the research questions. An important note is that the latter criterion involves a risk of bias in terms of subjectivity, since it relies on the researcher's interpretation of whether or not a paper is connected to the research question. Twenty-five papers were considered relevant and of sufficient quality for further analysis.

3.8.2. Comprehensive prescriptive study

To understand how the ConOps method can be used to design human-centric production systems, a comprehensive prescriptive study was designed combined with attempts to verify the methods used. The third stage of DRM, the Prescriptive Study stage, focuses on how to proceed to developing design support (knowledge, guidelines, checklist, methods, tools, etc.) in order to enhance, eliminate or reduce the influence of some of the critical factors found in descriptive studies (Blessing & Chakrabati, 2009a). Blessing & Chakrabarti continue: "Such a study is a purposeful activity with the resulting support or its concept as the end product, and is, therefore, a design task in itself. Creativity and imagination are required to develop effective and efficient design support. For this, a number of generic problem solving and development methods can be used". The study is performed as a Comprehensive PS, as it results in support that is realised to such an extent that its core functionality can be evaluated, compared to the Initial PS which describes the intended support, and a Review-based PS which evaluates the developed support without the researcher being involved. For this Comprehensive Prescriptive Study, the design guidelines and methods applied were primarily selected from Design Thinking and ConOps approaches. To grasp many perspectives from the organisation, and not only the engineering dimension, cross-functionality was identified as key in order to develop the demands and requirements from the stakeholders to the system. A total of 166 people participated in interviews and workshops, although they were not 166 individuals. Several people joined multiple workshops. The model used is based on the Systematic Prescriptive Study process, described in Figure 26.

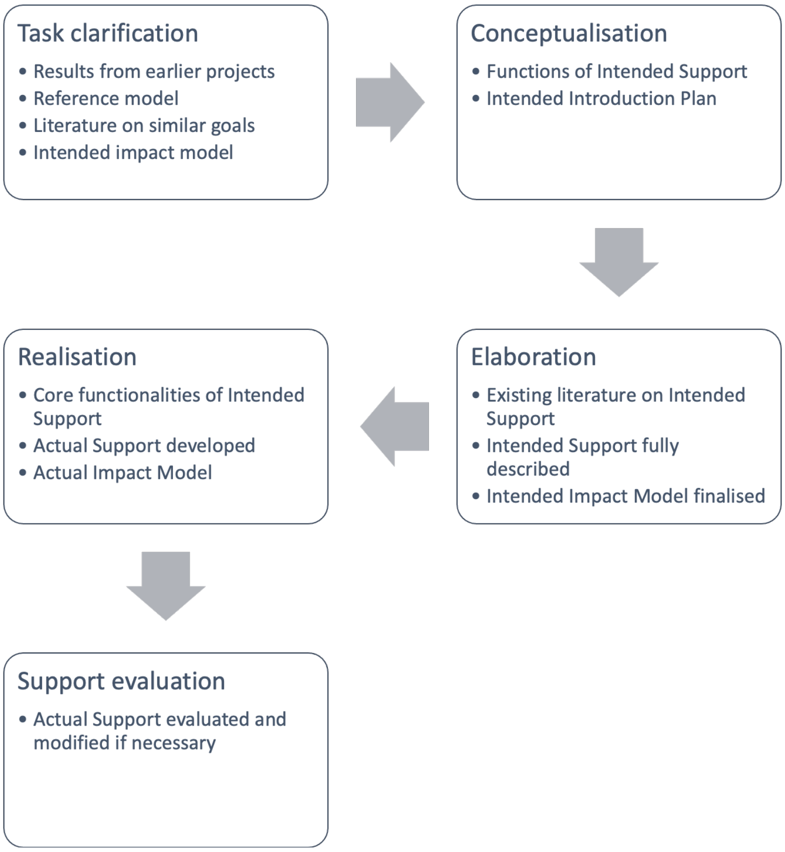


Figure 26: Main steps in the Systematic Prescriptive Study stage, from Blessing & Chakrabarti (2009)

3.9. Research approach - Paper E

Paper E consists of literature review and systematic prescriptive study process.

3.9.1. Literature review

A literature study was performed during the research process. The method of reviewing the literature varied throughout the process. Three databases were used: Scopus, Web of Science and Access Science with complements from Google Scholar. The keywords were combined into search strings with Boolean operators, together with a summary of the number of records that each search string produced, with results limited to peer-reviewed full text from the years 2015-2023. Snowballing was used in several instances. Figure 27 describes the areas for research contribution.

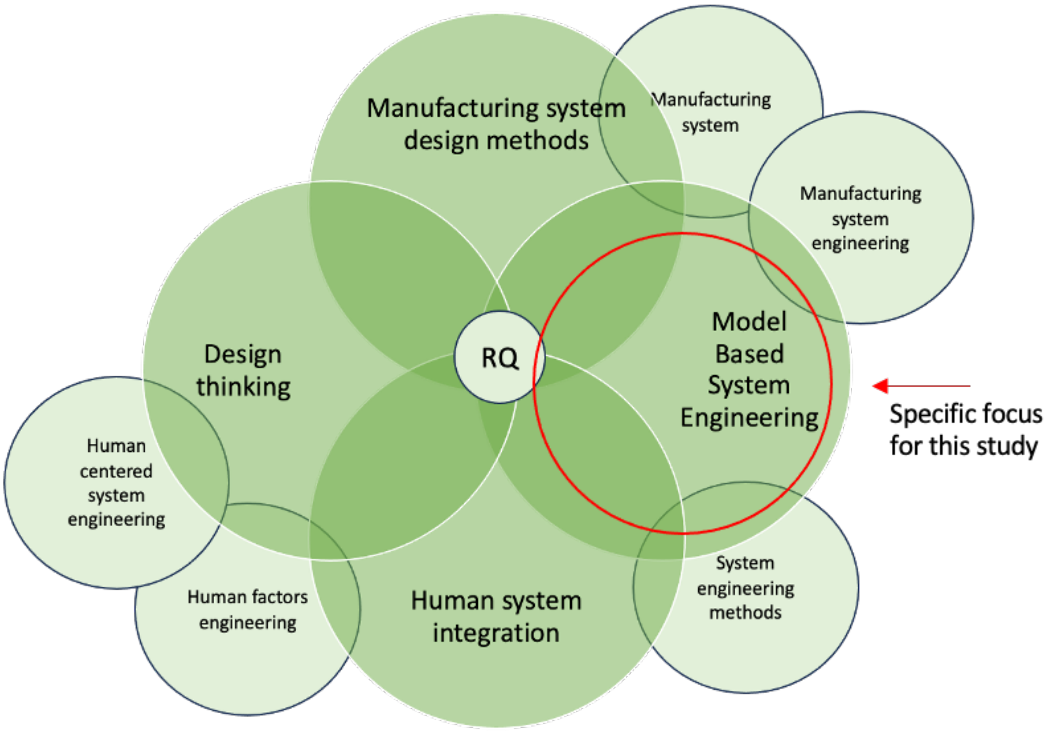


Figure 27: Areas for research contribution Paper E (ARC-diagram)

The search was limited to the title, abstract and keywords of the records and a selection of 35 articles were considered relevant, as described in Figure 28.

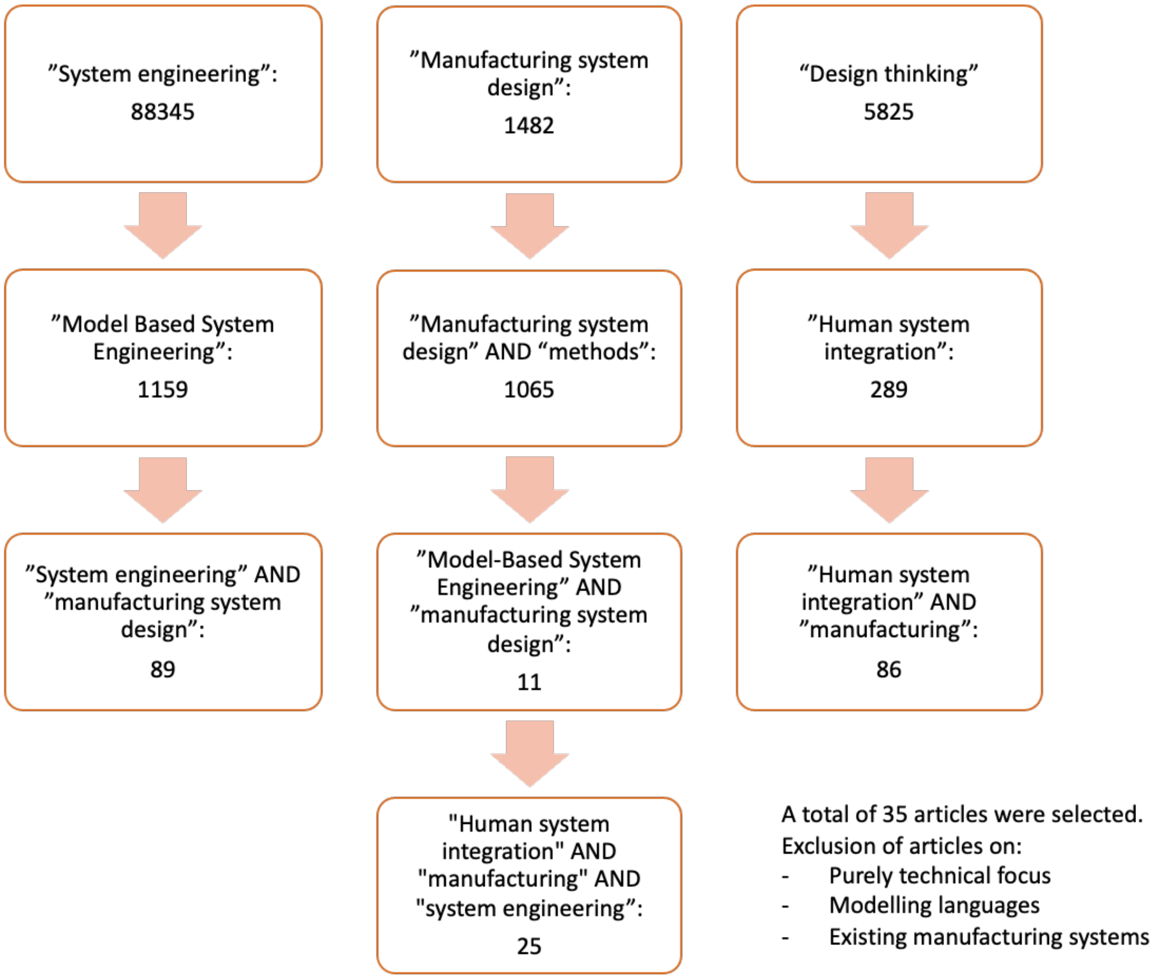


Figure 28: Search strings for literature review with a summary of the number of records in the results and a summary on how the 35 relevant articles were identified.

Since the same search strings were used in more than one database, duplicates occurred in the searches in the different databases. Where the titles were relevant, the abstract and keywords were read and added to the list of papers to be read in full. The main criterion for exclusion and inclusion was a connection to manufacturing industry or engineering. Articles focusing on pure technology, modelling languages and existing manufacturing systems were excluded. In addition, only published articles, conference papers, books and book chapters were included, and another criterion was a clear link to the research questions. Important to note is that the latter criterion involves a risk of bias in terms of subjectivity, since it relies on the researcher’s interpretation of whether a paper is connected to the research question. Twenty-five papers were considered relevant and of sufficient quality for further analysis.

3.9.2. *Comprehensive Prescriptive study*

To understand how Model-based Systems Engineering can be used to design human-centric production systems, a comprehensive prescriptive study was designed combined with attempts to verify the methods used. The study is performed as a Comprehensive PS, as it results in support that is realised to such an extent that its core functionality can be evaluated, as compared with Initial PS, which describes the intended support, and a Review-based PS, which evaluates the developed support without the researcher being involved. For this Comprehensive Prescriptive Study, the design guidelines and methods applied were primarily selected from Design Thinking and Model-based Systems Engineering approaches. To grasp many perspectives from the organisation, rather than only the engineering dimension, cross-functionality was identified as key in order to develop the demands and requirements from the stakeholders regarding the system. A total of 166 people participated in interviews and workshops, although they were not 166 individuals. Several people joined multiple workshops. The model used is based on the Systematic Prescriptive Study process, described in Figure 29.

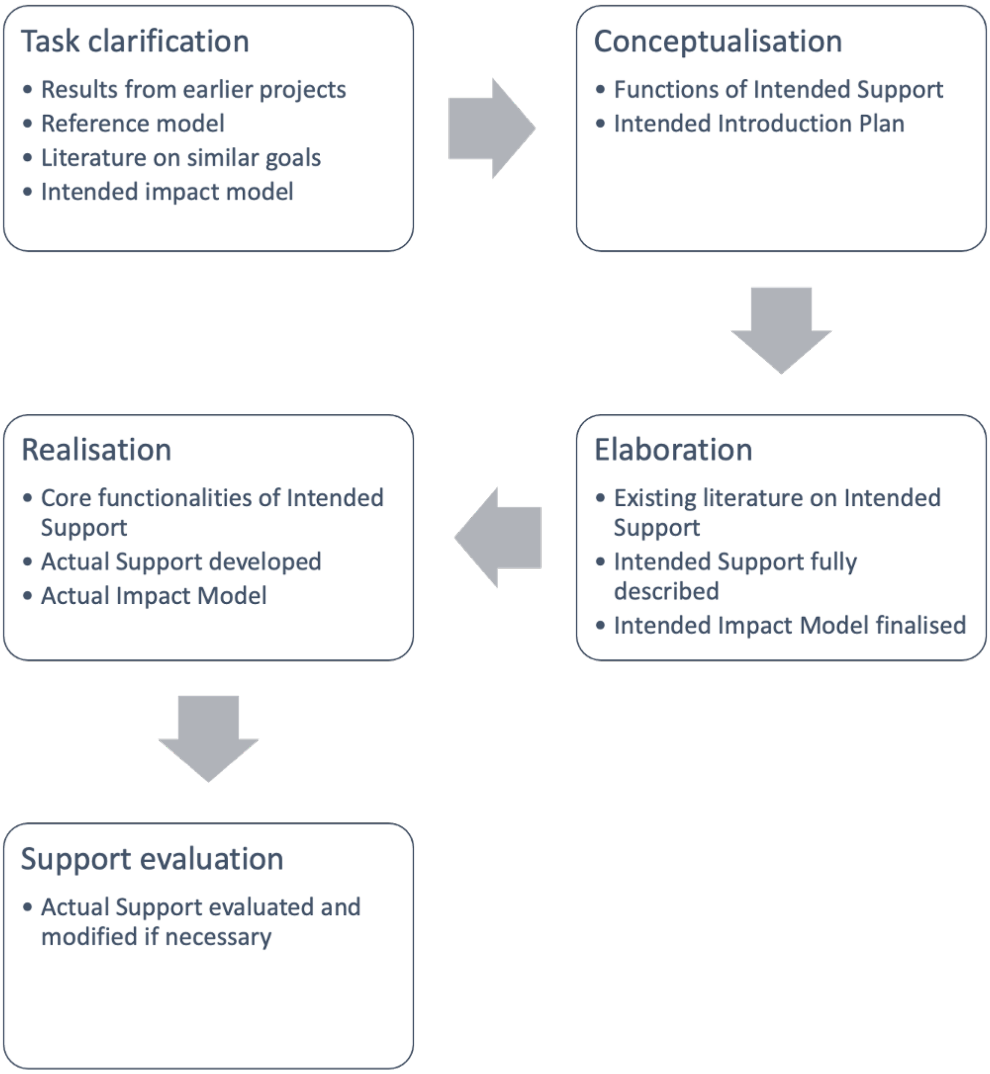


Figure 29: Main steps in the Systematic Prescriptive Study stage, from Blessing & Chakrabarti (2009)

3.10. Research approach - Paper F

Paper F consists of an Initial Prescriptive Study based on the findings from Paper D and Paper E. The project aims to set up a production system for battery assembly and distribution, including a circular flow of used batteries and the remanufacturing of these batteries. To understand how system engineering methods can be used to design human-centric production systems for novel products, an initial prescriptive study was designed which aims to describe the intended support. The Initial Prescriptive Study consists of the two initial steps in the Prescriptive Study stage, as seen in Figure 30.

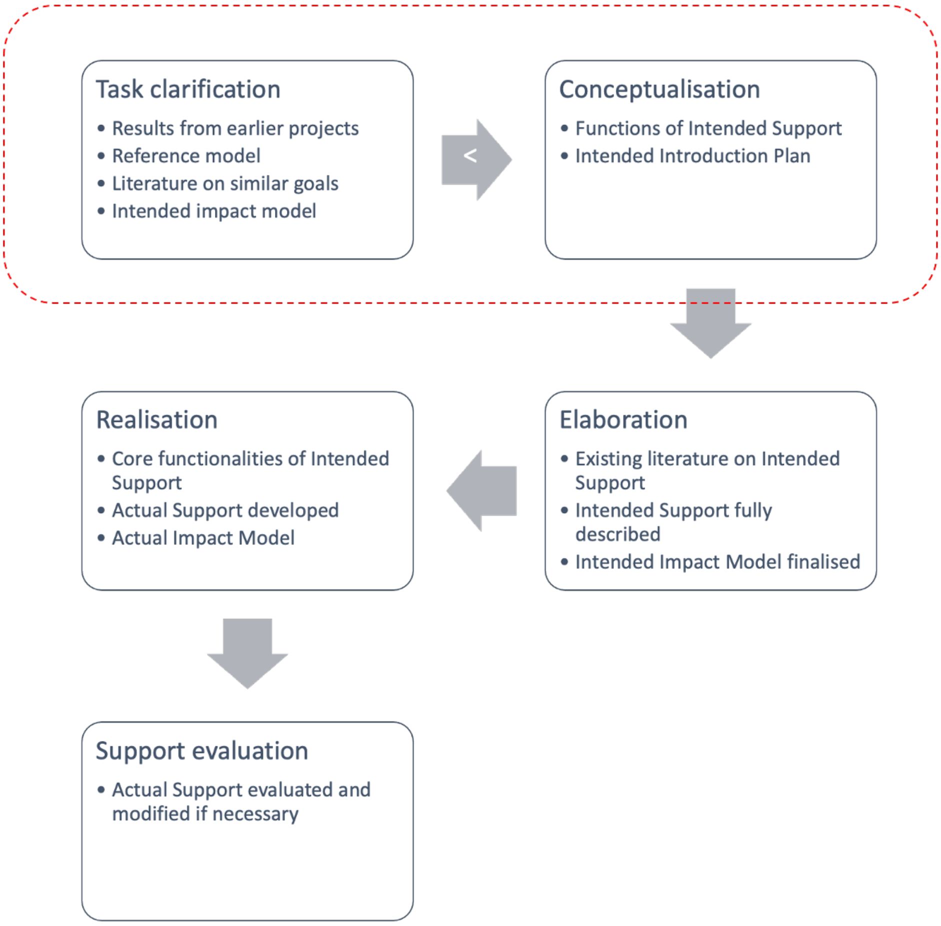


Figure 30: Initial Prescriptive Study consist of the two initial steps in the Prescriptive Study stage, from Blessing & Chakrabati (2009)

4. Results

This chapter presents a summary of key takeaways from the appended papers and each paper individually, which are used for the analyses to answer the research questions.

The research results, development and validation have been presented in six core publications (Paper A through Paper F), which form this thesis.

4.1. Summary of appended papers

The main contribution presented in this thesis is published in six academic publications appended in the second part of this thesis. A summary of relevant parts and key takeaways of each publication follows. Figure 31 describes the logic of the research and key takeaways for each publication to support the logic.

Paper A	Validating the importance of studying production systems engineering design State of Practice regarding maintenance aspects of equipment acquisitions
Paper B	Studying production systems engineering design State of Practice regarding maintenance aspects of equipment acquisitions
Paper C	Studying systems engineering State of Art
Paper D	Identifying research gaps in production system design Applying systems engineering method of ConOps to design human-centric production system for electric products
Paper E	Identifying research gaps in production system design Applying systems engineering method of MBSE to design human-centric production system for electric products
Paper F	Combining Paper D and Paper E to a framework (VDHCP)

Figure 31: The logic of the research with key takeaways for each publication

4.1.1. Paper A: Visualising waste and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations

To make sure the research presented in this thesis and onwards would focus on a real industrial problem, a pre-study, documented in Paper A, was performed to identify the costliest production disturbances that the case company was experiencing. A new method, called end-to-end cost deployment, was tested to identify these most significant issues. The pre-study showed that equipment break-down within the maintenance field was one of the most expensive factors. Reliability may be defined as the probability that a system or product will perform in a satisfactory manner for a given period when used under specified operating conditions.

Paper A key takeaways: Reliability of equipment is of major concern for the case company. The importance of investigating systems engineering state of practice is validated. From that result, the rest of the research involved addressing the equipment acquisition process and the community performing this process.

4.1.2. Paper B: Reducing professional maintenance losses in production through efficient knowledge management in machine acquisitions

Paper B sought to understand the barriers preventing knowledge from current production disturbance in terms of equipment break-down cost from being fed back to the equipment acquisition process. This was done through interviews in connection with four projects where the same equipment was acquired again. The study found that the barriers are more in the individual and organisational dimensions and less in the technological dimension.

Paper B key takeaways: On studying the state of practice in production equipment acquisitions, findings show that barriers exist to capturing, sharing and re-using maintenance system requirements. The barriers are more in the individual and organisational dimensions and less in the technological dimension.

4.1.3. Paper C: Drivers and barriers to implement digitalisation in engineering processes – a literature review

Paper C aims to perform a systematic literature review to explore drivers and barriers to implementing digitalisation in engineering processes from a socio-technical perspective. The identified general barriers are cyber security, lack of skills, lack of standards, large investments and resistance to change.

Paper C key takeaways: Studying the state of the art in systems engineering developments, the main change drivers were increased product complexity, servitisation, data-driven design and engineering productivity, while the main barriers to change were culture, excess amount of data, integration of tools, cyber security and data quality.

4.1.4. Paper D: Using Concept of Operations to design human-centric manufacturing systems for novel products. A prescriptive study, Part 1.

Paper D covers a case study that uses the systems engineering method Concept of Operations and Operational Concept for the design of a production system for a novel product. A comprehensive prescriptive study was designed combined with attempts to verify the methods used. The case study applies design methods defined in ISO/IEC/IEEE 15288. A total of six workshops, development of Concepts of Operations, three levels of Operational Concept, and two validation studies are documented. A total of 166 persons (not 166 unique individuals, however) participated, and 15 unique individuals participated in the validation workshops.

Paper D key takeaways: The analysis shows that the Concept of Operation method addressed gaps identified in literature, (1) the lack of systematic and effective systems engineering design *methods in production system design, and (2) the lack of inclusion of human aspects in the production system design. With this method, system requirements from human-centric perspective could be identified in early stages.*

4.1.5. Paper E: Using Model-Based Systems Engineering to design human-centric manufacturing systems for novel products. A prescriptive case study, Part 2.

Paper E covers a case study that uses the systems engineering method Model-Based Systems Engineering for the design of a production system for a novel product. A comprehensive prescriptive study was designed combined with attempts to verify the methods used. A total of six workshops, development of models to define requirements to select concepts and two validation studies are documented. A total of 166 persons (not 166 unique individuals, however) participated, and 15 unique individuals participated in the validation workshops.

Paper E key takeaways: The analysis shows that the MBSE method addressed gaps identified in literature, (1) the lack of systematic and effective systems engineering design methods in production system design, and (2) the lack of inclusion of human aspects in the production system design. With this method, system requirements from human-centric perspective could be identified in early stages.

4.1.6. Paper F: A Proposed Framework Using Systems Engineering To Design Human-Centric Manufacturing Systems For Novel Products To Reduce Complexity And Risk

Paper F aims to propose a framework based on system engineering for the production system engineering community. The framework is based on two previous case studies which are under review for publication and which concern the design of a battery assembly plant. The research model is design research methodology as an initial prescriptive study. The task of the framework was clarified on the basis of a literature review, the previous case studies and the problem statement, which is defined as "Develop a systematic and effective framework to help experienced manufacturing engineers take into consideration human-centric factors when designing cyber-physical production systems for novel products". From this, a requirements list was drawn up explaining what the framework should contribute. The list has since been conceptualised. The framework was selected for development in accordance with the ISO/IEC/IEEE 15288 (2023) standard using a Concept of Operations and Model-based Systems Engineering in a workshop setting, with a focus on visualisation, understanding the practical and emotional needs of the client and using prototypes or physical models. The framework was validated in a workshop covering Stage 1 to Stage 4 with the battery cell plant management team, a total of twelve senior cross-functional executives.

Paper F key takeaways: The framework was validated by the senior management team (12 unique individuals) of the battery cell project and showed promising results in capturing requirements from human-centric perspective in early stages when designing human-centric production systems for electric products.

4.2. Paper A: Visualising wastes and losses in automotive production flows (across multiple plants and organisations) for increased accuracy in improvement prioritisations

4.2.1. Purpose

The purpose of this study was to ensure the continued research focused on a significant industrial problem area. It was also a test to explore new ways to identify, quantify and visualise losses to be able to prioritise improvement efforts correctly. This paper tests the potential to collect this data through the entire supply chain where several plants and operations are involved. This study was performed in collaboration with three plants and one logistics provider. One important delivery from the paper was to identify the main loss in an extended supply chain and make it comparable regardless of the size of the plant or the complexity of the product.

4.2.2. Results

The data across the entire flow is converted to one 11 litre cylinder head equivalent by using the normalisation model. The results are visualised in Figure 32. The data is normalised to be comparable regardless of the size of the plant or the size of the product.

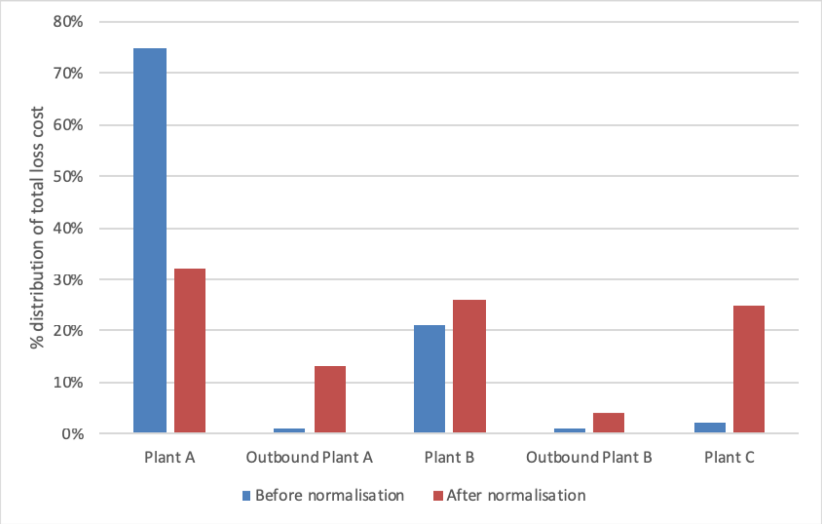


Figure 32: Comparing the distribution of total cost loss before and after normalisation for each step in the process

The bars are very different before and after normalisation of the observations. After the removal of factors stemming from the size of the plant and the factor of share of production volume, the chart below gives a more accurate picture of the loss distribution for *a specific part*. By using this normalisation factor, it is possible to consolidate the losses from all plants and the transports between them and get a meaningful visualisation of the losses in this entire flow, which is illustrated in Figure 33.

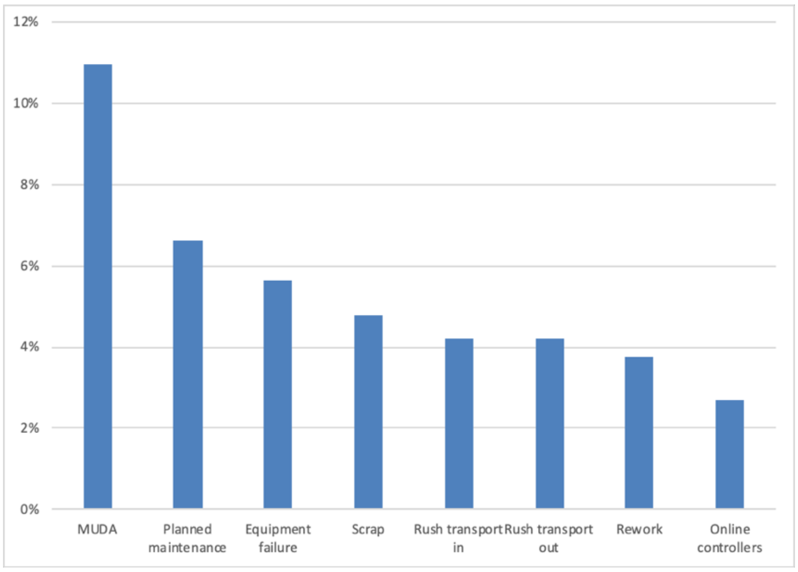


Figure 33: Top eight losses in the supply chain flow using normalised data (two losses were considered one-timers and are not part of the graph)

The graph visualizes the consolidated top eight losses for this particular flow with three plants. Two losses were considered one-timers and are not part of the graph. The profile corresponds to the assumption that since all sites are labour-intensive, non-value adding activities performed by operators (muda) would be a significant part of the losses. Moreover, this part is a machined part with advanced equipment which makes the maintenance losses natural. This study confirms this assumption as well. The top loss in the flow under this study is muda, the second-highest loss is caused by planned maintenance and the third-highest loss contribution is by equipment failure. As per the cost deployment methodology, the top three are to be assigned resources to initiate improvement and loss reduction activities. Thus, this result is in par with the research question stated and the cost deployment methodology. These results provide a basis for recommendations to tackle the top losses. These top eight losses correspond to 43% of the total losses identified, which shows that by focusing the improvement efforts on the top losses, a large part of the total loss costs is attacked. Another finding is that even if the logistics flow only captures the cost of rush transports and not the other logistics-related costs, both in- and outbound rush transports are in the top eight chart.

When the graphs are compared, in Figure 34, it is clear that when the data is compensated for size of plant and complexity of product, the loss profile for the cylinder head equivalent changes.

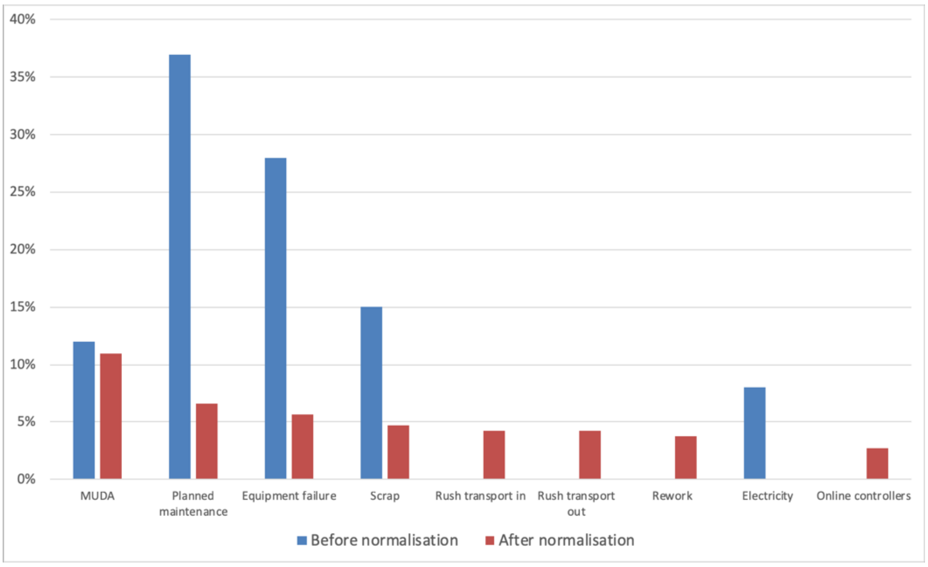


Figure 34: Comparison of loss data before and after normalisation, specifically planned maintenance, shows a large reduction through normalisation. (Together with equipment failure and Scrap).

4.2.3. Conclusions

The data shows that when identifying the major losses for a specific product, this method can be used. Paper A shows that maintenance is a significant cost factor for the studied process, regardless of size of the organisation or complexity of the product, as described in Figure 35.

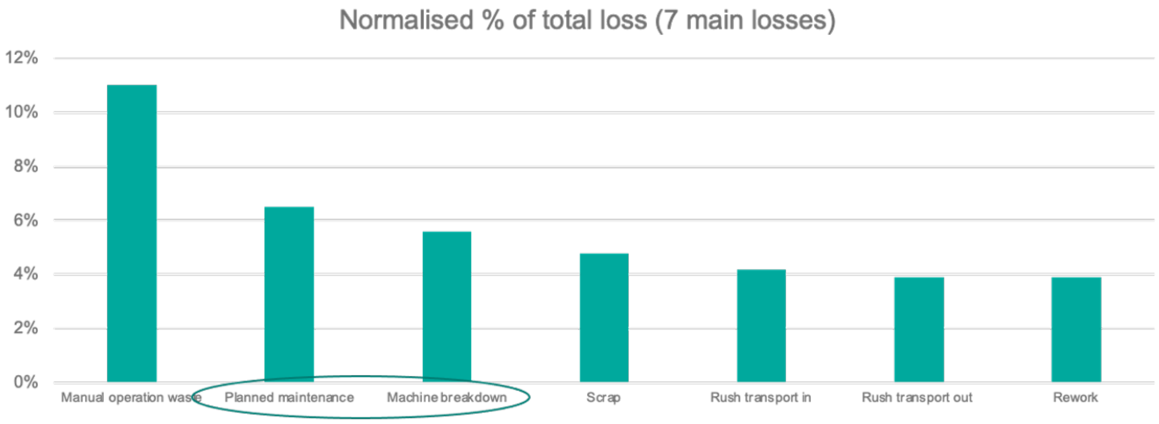


Figure 35: Maintenance losses are a significant contributor to the top losses

4.3. Paper B: Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions

4.3.1. Purpose

Based on findings in Paper A, a qualitative study was designed to understand the barriers to capturing, sharing and re-using knowledge related to the acquisition of production equipment, from a maintenance perspective.

4.3.2. Results

Regarding the definition of equipment acquisition, which was called Early Equipment Management (EEM) in the case company, in plant A it was defined as being a structured framework for procuring equipment by using previous experience. Three of the interviewees mention that it is a process where lessons learned from previous projects should be included. All of them describe EEM as a structured process for procuring equipment. As one interviewee states: “It’s a good framework for letting you what do and when. It’s a way of working that I think works quite well.” In plant B, EEM was defined as a structured framework for achieving improvements in the new equipment. Moreover, all of them describe it as a structured process for procuring equipment. Only one interviewee stated that working with EEM was a possibility for inputs of improvements from current production. “For me, the principle of EEM is that when we are in the process of buying a new machine, we look at previous projects for any improvement points we can incorporate in this purchase.” In plant C, EEM was defined as a structured framework for procuring equipment with the highest possible up-time, by involvement of different functions. Only one interviewee described EEM as a process with focus on longevity: “The philosophy is to find out how to maintain your equipment with the highest possible level of uptime and the minimum downtime. That’s what EEM truly is.” The interviewee also expressed concern about the lack of understanding of the EEM philosophy among colleagues. “Most people don’t understand EEM; most people believe more in the old form of preventive maintenance where you set a schedule for tasks and that’s it. Now we’re in a more competitive situation and need to have as much available time as possible for production.”

Regarding the objective of EEM, plant A focuses on satisfying the production department, referred to as the customer, by delivering better equipment. Indicators such as “reliability” and “availability” are often mentioned as measurements for better equipment. One project manager stated specifically that “the project should meet the targets in terms of cost and performance, as well as other values such as environmental, safety and ergonomic aspects.” Plant C mentions that the objective of EEM is to include all the departments’ different requirements, as well as to deliver better equipment. The electric maintenance technician defines better equipment as having more up-time and less down-time. Plant B instead focuses on delivering equipment without disturbances that produce in line with expectations, and aspects such as knowing what do to and minimising risk are also mentioned. One interviewee stated that the objective is for the equipment to perform better as a result of the time invested in making sure the project has captured all knowledge and experience. One interesting observation is that all interviewees regarded the specific project as the objective, rather than the success of all projects from a systemic view, which is defined in the theory as the organisational knowledge value stream.

When talking about the challenges of EEM, all three plants find the high workload or limited amount of time challenging. Plant B finds the lack of resources and competence restricting. As one interview mentions, “We have the processes described very well, but the trigger to buy a machine often comes too late, which makes the entire purchase stressed.” Another insightful comment was: “This was very frustrating at the beginning, but as I learn more, I realised how difficult it is for everyone to take the necessary decisions in time.” Plant A also finds skills a challenge, specifically knowing how to know what skills to include in the project in order to achieve success. “The main challenge is having a clear specification from the requester, and for the requester to the rights skills to know what he or she needs, which not always the case.” Regarding the time aspect, one person from Plant A states: “We are rather conservative as we don’t always have time to test new technologies or new suppliers”. The softer aspects are also mentioned: “To make a successful project, you need not only skills but also engagement and commitment from the people involved.” Individuals from plant C mention difficulties with the high workload and getting other people in the organisation to understand the philosophy. A maintenance representative describes one of the main challenges: “If you build a better house, it lasts longer so most people have a job to do. Project managers have to be on time and under budget, that’s their philosophy. But that kind of collides with the holistic view, it kind of collides with trying to make this the best machine possible.” The interviewee says that the main challenge is campaigning and making others understand the philosophy. This interviewee also highlights the conflict between the traditional view of a project, time and budget, and the holistic view of EEM.

The interviews show that several process tools are used to ensure that the right knowledge is brought into the project. A majority of the interviewees describe also performing other activities such as study visits, benchmarks and training in addition to the process discussed. Involvement of operators, maintenance and technicians is achieved by engaging them through interviews and the creation of a list of improvements. Several of the interviewees refer to a lack of knowledge of EEM and the process of capturing knowledge and experience. It is mentioned that the level of knowledge has decreased in recent years and that it is difficult to find the appropriate knowledge.

Table 6 shows the methods used to capture knowledge today as input for the EEM process and what type of knowledge they capture.

Table 6: Tools used in the case company to capture and transfer knowledge.

Tool	***Knowledge type***	***Plant A***	***Plant B***	***Plant C***
Emergency work order (EWO)	Explicit	X	X	X
Human Error Root Cause Analysis (HERCA)	Explicit			X
White book	Explicit		X	X
Industrial Project Assurance Plan (IPAP)	Explicit	X		
Technical specification	Explicit		X	
Scope of supply	Explicit	X	X	
Operators’ list	Explicit	X		
Benchmark	Implicit	X		X
Study visit	Tacit	X	X	
Training	Tacit	X	X	X

Regarding the barriers to effective knowledge management, a few aspects were mentioned specifically. For example, on the organisational level, when asked how knowledge is captured before the next machine purchase, one respondent stated: “There’s no way to capture knowledge, other than me telling my colleague that that the drive is horrible. If we ever buy this machine again, it would just be me verbally saying something.” Others mention that it is more from an individual basis that people express a willingness to learn, rather than due to a systematic approach from the organisation: “We asked some of the younger engineers if they wanted to shadow the process as volunteers.” From the technological point of view, it was mentioned that the systems are perhaps not built up in the most useful way for the engineers: “We currently have all requirements in one system. It would be useful to have one requirement list for maintenance, one for safety, one for quality, etc.” Another example from the technological perspective regards documentation: “We got the information too late, and when it arrive it we discovered it was sorted in the wrong structure.” Again from the organisational perspective, one interviewee says: “Fifteen years ago we had more skilled people than we do today. They’ve either left the company or have new roles in the company. We’ve lost a lot of competence.” This is corroborated by another statement: “One topic in my area of expertise has been in operations for several years. The person running it retired and we didn’t think to transfer that knowledge because the process seemed to be working. When we started getting issues, we had nobody who could solve it. The solution was to bring in external expertise.” Several interviewees’ responses suggest that that competitiveness is not a big issue, either internally or externally. It seems they are not reluctant to benchmark and consult with other plants or departments. “We heard another company had bought the same machine, so we went to them and had a look.” Some responses suggested a lack of trust in others’ credibility or knowledge: “We used other oils than advised by the supplier and had a lot of problems.” The respondents ranked the items in Table 7 as barriers to knowledge management (the total number of respondents indicating this as a barrier was more than 3):

Table 7: Identified knowledge barriers in the study

Individual	**Organisational**	**Technology**
Time	Strategy	IT support
Awareness	Directions	
Explicit vs tacit	Support	
Capture	Low priority	
Trust	Infrastructure	

4.3.3. Conclusions

Paper B has identified the main barriers to capturing, sharing and re-using knowledge related to production equipment acquisition from a maintenance perspective. The main barriers are in the individual and organisational dimensions and less in the technological dimension. In the individual dimensions, the main barriers were identified as lack of time to work on knowledge management, lack of awareness that it could be important, lack of capability to transform the knowledge from tacit to explicit, and lack of trust in the knowledge stored. In the organisational dimension, the main barriers were identified as a lack of strategy from a company perspective on how to address knowledge management, and hence insufficient directions and support from management to focus on it. It was perceived as a low priority in the organisation. Finally, a lack of infrastructure was identified as a barrier to working actively on knowledge management from an organisational perspective. There is a link between the infrastructure barrier and the only technological barrier that was highlighted: a lack of IT support to facilitate knowledge management processes.

4.4. Paper C: Drivers and barriers to implement digitalisation in engineering processes – a literature review

4.4.1. Purpose

The purpose of Paper C was to investigate the academic research gap. The aim of this systematic literature review was to explore drivers and barriers to implementing digitalisation in engineering processes from a socio-technical perspective.

4.4.2. Results

A total of 26 unique barriers were identified and, with the aim of providing an understanding of the relative importance of these barriers, the frequency of mentions across the papers was noted in Figure 36.

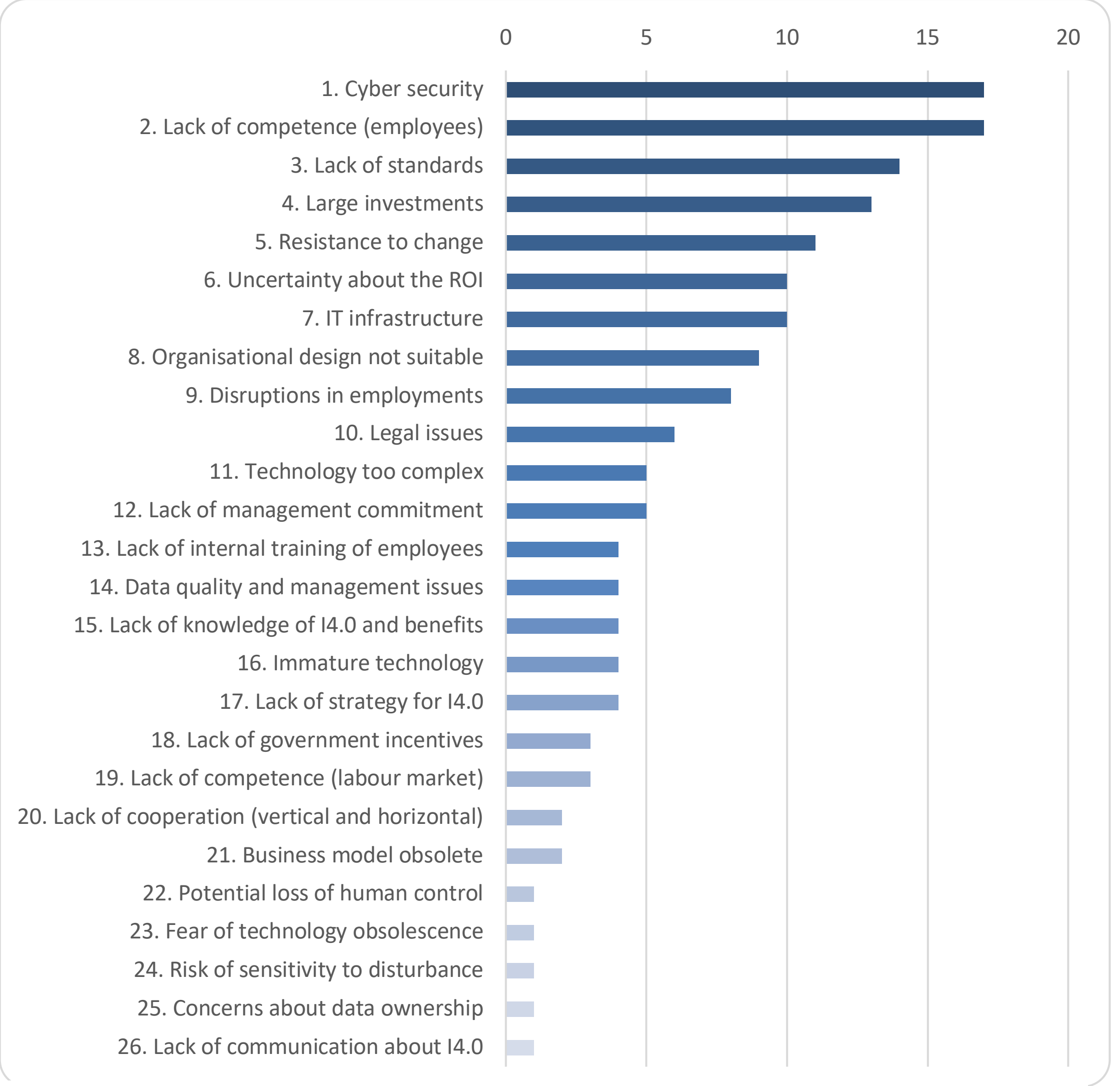


Figure 36: Frequency of mentions of the barriers identified in the selected 28 papers.

4.4.3. Conclusions

The identified general barriers to implementing digitalisation in engineering companies were cyber security, lack of skills, lack of standards, large investments and resistance to change. For the engineering processes, the main drivers were increased product complexity, servitisation, data-driven design and engineering productivity, with the main barriers being culture, excess amount of data, integration of tools, cyber security and data quality. The study shows the complexity of the challenge, and that it is not only technology that is the top barrier.

4.5. Paper D: Using Concept of Operations to design human-centric manufacturing systems for novel products. A prescriptive study, Part 1.

4.5.1. Purpose

The purpose of Paper D was to explore how systems engineering design support methods of *Concept of Operations and Operational Concept* (Fairley & Thayer, 1997) can be used to reduce complexity and risk in the design of a new battery manufacturing system with a human-centric focus.

4.5.2. *Results*

To mitigate the challenges identified in the projects, proposals for methods going forward were presented and ConOps was selected. High-level Task clarification was developed from the Project goals, the Engineering goals, Goals break-down and Intended Impact Model as described in Figure 37, highlighting the focus of Paper D vs Paper E.

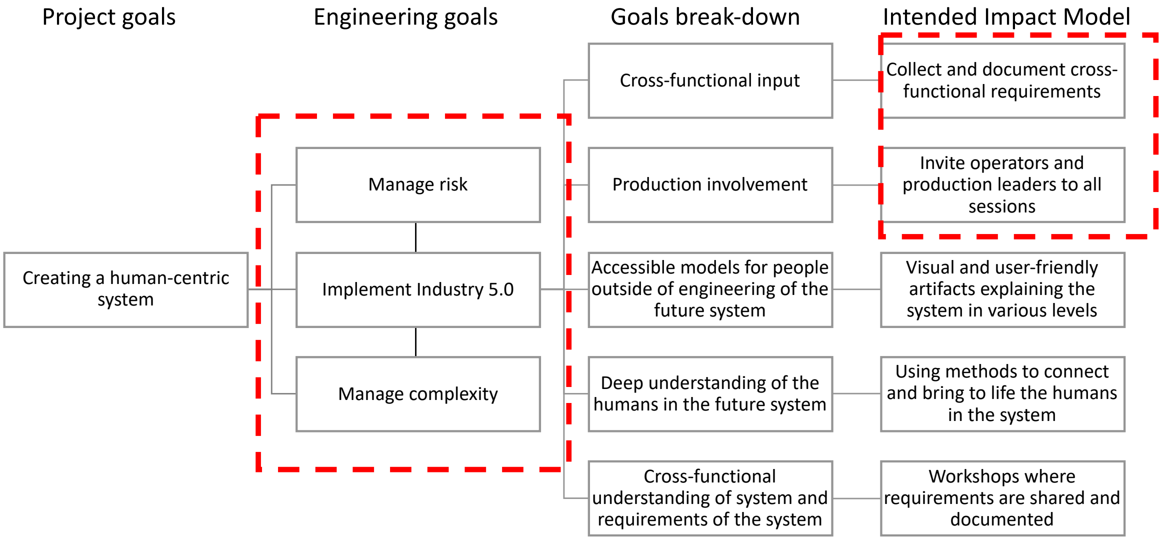


Figure 37: Logic of development of Intended Impact Model for the Comprehensive Predictive Study. The engineering goals were formulated differently in Paper D vs Paper E, and are highlighted to support the reader.

The Intended Support Description was generated from the task clarification documented in the Intended Impact Model. The Intended Support Description describes the support in terms of the need or problems addressed, the goals and objectives of the support, its elements, how it works, the underlying concepts, theory, assumptions and rationale, and how it is to be realised. The Intended Support Description is described in Table 8.

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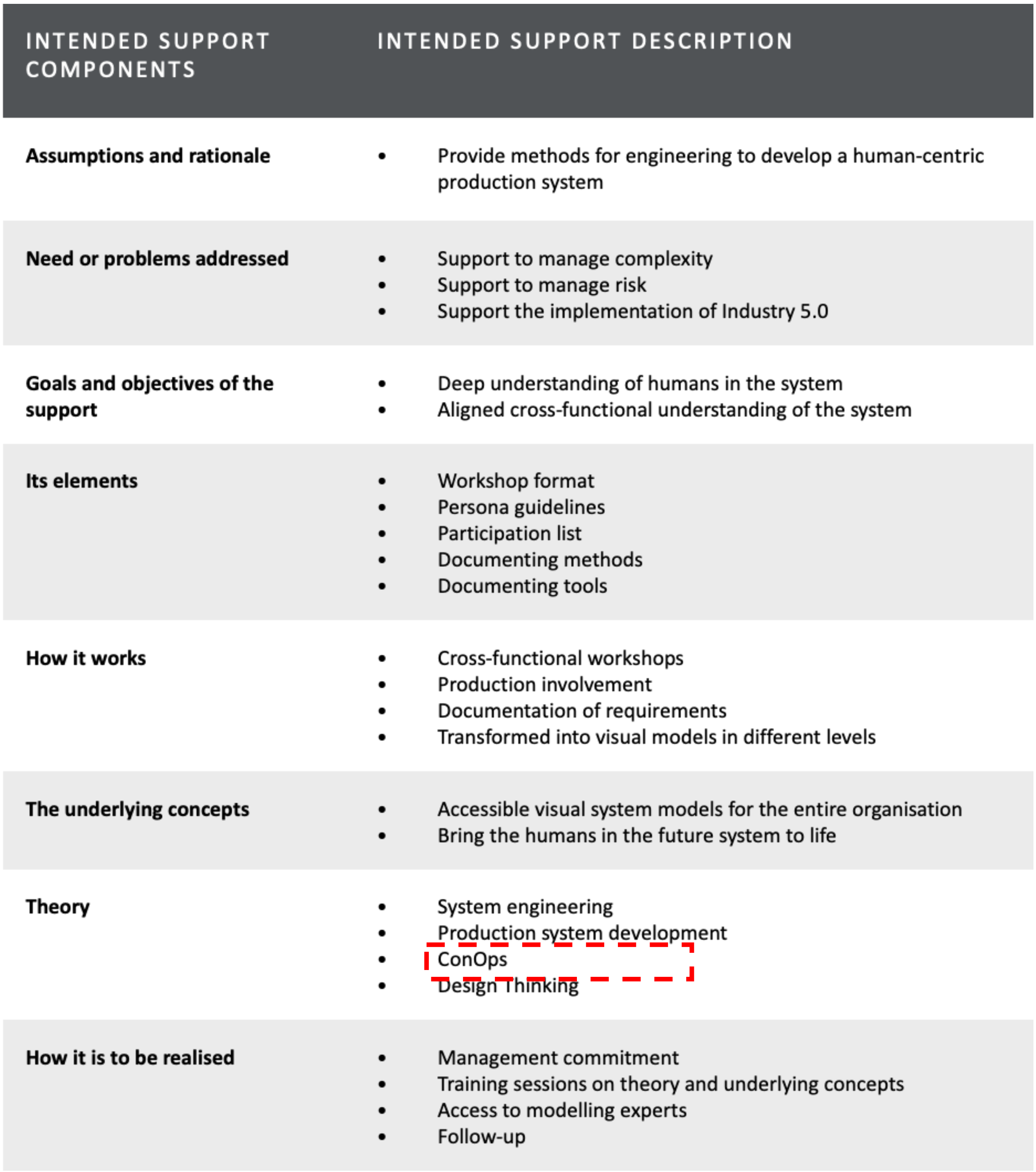
Table 8: Intended Support Description. The engineering goals were formulated differently in Paper D vs Paper E, and are highlighted to support the reader.



INTENDED SUPPORT COMPONENTS	INTENDED SUPPORT DESCRIPTION
Assumptions and rationale	• Provide methods for engineering to develop a human-centric production system
Need or problems addressed	• Support to manage complexity • Support to manage risk • Support the implementation of Industry 5.0
Goals and objectives of the support	• Deep understanding of humans in the system • Aligned cross-functional understanding of the system
Its elements	• Workshop format • Persona guidelines • Participation list • Documenting methods • Documenting tools
How it works	• Cross-functional workshops • Production involvement • Documentation of requirements • Transformed into visual models in different levels
The underlying concepts	• Accessible visual system models for the entire organisation • Bring the humans in the future system to life
Theory	• System engineering • Production system development • ConOps • Design Thinking
How it is to be realised	• Management commitment • Training sessions on theory and underlying concepts • Access to modelling experts • Follow-up

The sequence of the workshops as well as the set-up of each workshop were designed to collect data for both Paper D and Paper E simultaneously. The Intended Impact Model and Intended Support Description were iterated and an Intended Introduction Plan was generated, consisting of six workshops, as seen in Figure 38.

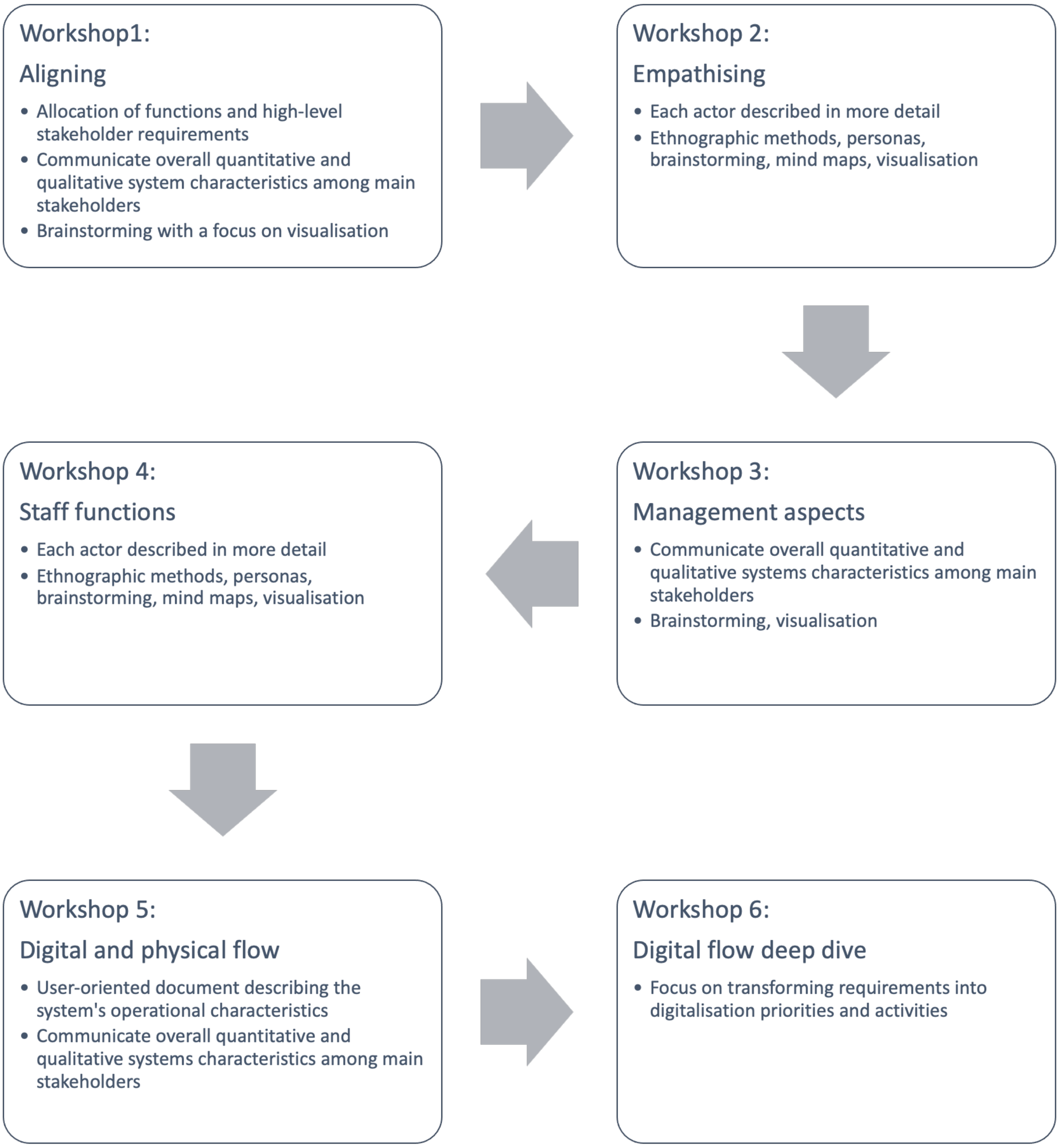


Figure 38: Intended Introduction Plan consisting of six workshops with the aims for each workshop described (same approach for Paper D and Paper E).

The workshops were designed to be three to four hours long and with the format described in Figure 39.

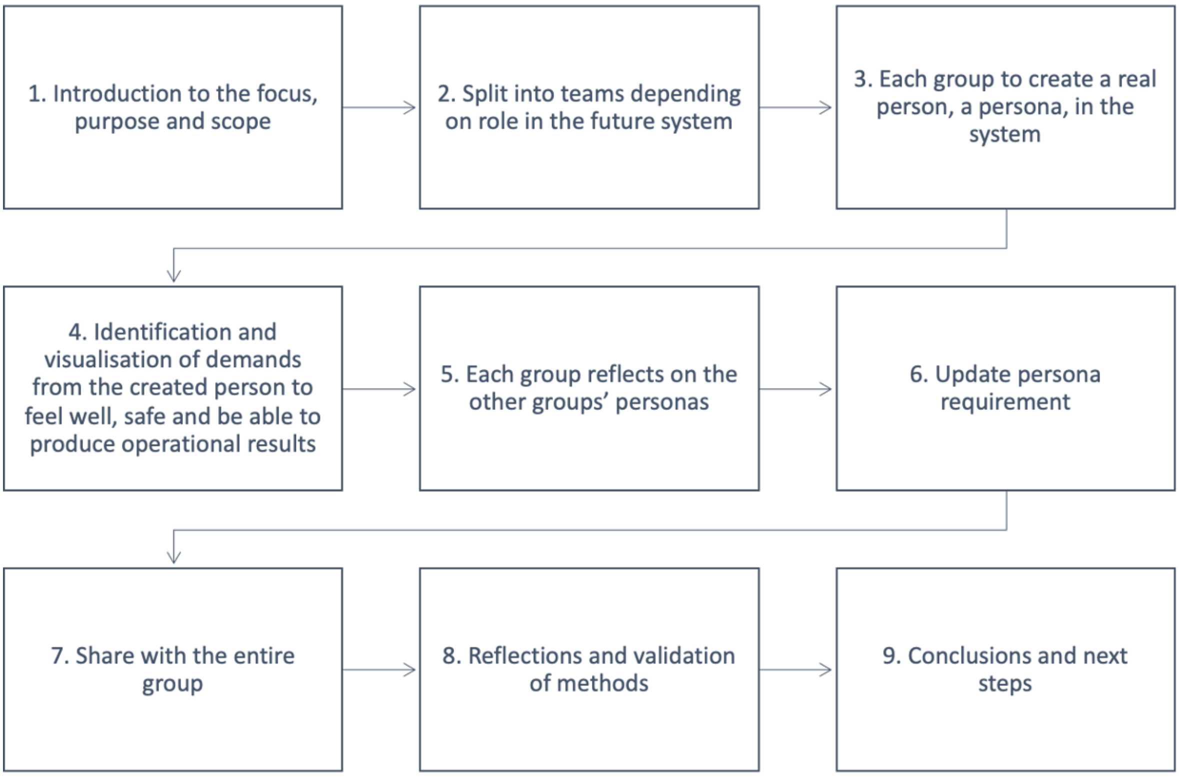


Figure 39: Workshop design for the six workshops (same approach for Paper D and Paper E).

The focus of the Intended Design Support is to ascertain how to get a satisfactory quality of input from all actors in the future system, hence the documentation and visualisation of the models were to be performed by the researchers and experts. In the realisation phase, the core functionalities of Intended Support, Actual Support developed and Actual Impact Model are elaborated on.

The input from the developed workshop framework was used to develop and refine the ConOps and OpsCon with different levels of abstraction, as well as to reuse some of the already created model presentations. The ConOps was used to gain a shared picture throughout the organisation of how the business will operate. The levels of ConOps and OpsCons are described in Figure 40, where image A is ConOps on an enterprise level, image B is ConOps from a production facility perspective, image C is OpsC level1 and image D is OpsCon level 2.

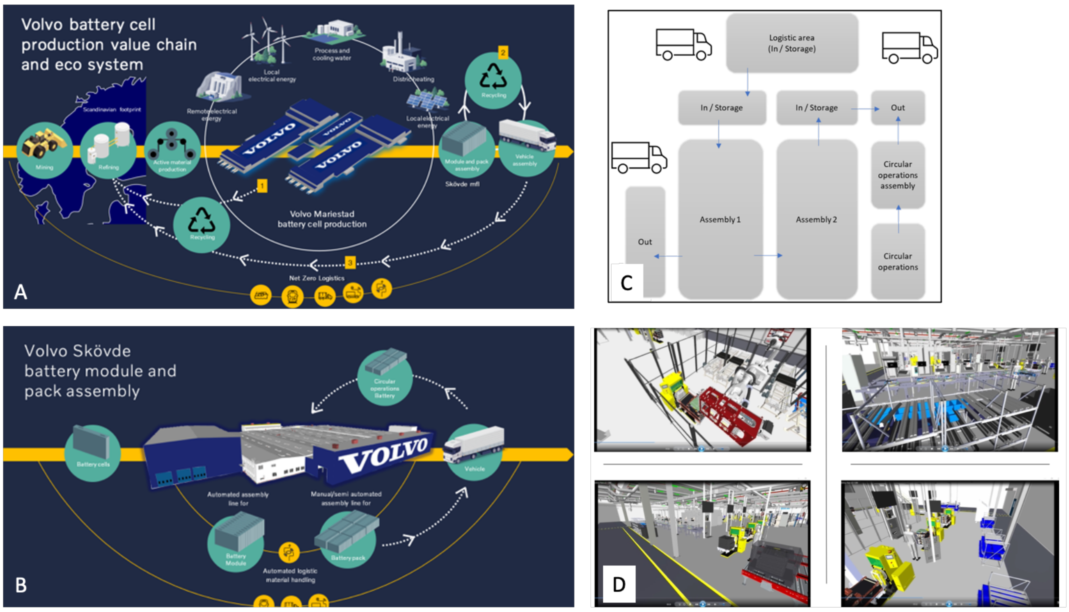


Figure 40: Image A is ConOps on enterprise level, image B is ConOps from a production facility perspective, image C is OpsCon level 1 and image D is OpsCon level 2.

The fulfilment by the Actual Design support to the Engineering goals are described in Table 9.

Table 9: Fulfilment by the Actual Design Support to the Engineering Goals

		Total	**Yes**	**No**	**Confirming statement (selection)**	**Challenges**
Engineering goals	Manage complexity	15	14	1	*"The collaboration and brainstorming in the workshops make us build our reasoning and makes the whole system better"*	*"Perhaps it is not detailed enough to just have workshops of this brainstorming characteristics"*
	Manage risk	15	15	-	*"This method helps us to identify risks early"*	*Not mentioned*
	Implement I5.0	15	15	-	*"This is human centric for real! To start from a specific person's needs in the flow / system".*	*Not mentioned*

The fulfilment by the Actual Design support to the Intended Impact Model are described in Table 10.

Table 10: Fulfilment by the Actual Design Support to Intended Impact Model

Intended impact model	**Confirming statement (selection)**	**Challenges**
Collect and document cross-functional requirements	"With this way we can develop more precisely our concepts" , "A very good way to document things we only talked about before", "Great to work cross-functionally like this", "Great to mix competences and aspects"	"It takes a while to understand the framework", "Difficult to get down to the details".
Invite operators and production leaders to all sessions	"With better methods like this, better collaboration and focus on flow we can minimise the risks", "I feel that I can influence the system and my future"	
Visual and user-friendly artifacts explaining the system in various levels	"This way makes it easier to understand" "This helps us understand the overarching ideas to be used in our production preparation", "It is a great way to visualise the life in the plant", "It was great to see the connections in the system"	
Using methods to connect and bring to life the humans in the system	"(...) is a way to make the person in the system more real", "We were missing the people focus before", "This way of working is great: we are breaking down something huge into manageable slices. This makes us feel that we are making progress and not standing still worrying".	
Workshops where requirements are shared and documented	"Collects and simplifies demands, as well as makes them more concrete", "I learned things I didn't consider before"	

4.5.3. Conclusions

The Design Support concept method to develop Concept of Operations was developed and delivered three artefacts on three levels of abstraction. This approach addressed issues identified in literature that complement the existing methods with new perspectives which encouraged creativity and cross-functionality. The approach supported the transfer of knowledge within and between development teams. The approach provided support in building models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. This approach supported the inclusion of humans in the systems right from the beginning, thus addressing the issue often seen in engineering of treating human aspects as an afterthought. Through this approach, several aspects were identified that had not been addressed, and work groups were set up to design solutions. The effectiveness of using the approach is difficult to assess completely as some of the expected effects, such as fewer problems (at least of the targeted problems in requirements), cannot be used as evidence until years later. However, it was possible to assess the participants' immediate feedback and responses, e.g. regarding engagement. The main learning from the interviews with the workshop participants is that all except one person felt that using these methods helps to manage complexity. It was also appreciated as being more rigorous in terms of documentation than previous projects, since one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Regarding the management of risks, the input was equally supportive. For instance, it was stated that this method helps identify and mitigate risks early in the project. Participants mentioned the importance of gaining an overview that they had previously lacked, and the importance of cross-functionality, collaboration and flow thinking supports this finding. It was also stated that with this approach, concepts can be developed more precisely and demands become more tangible. Some participants said that it takes some effort to understand the methods, but that using a more intuitive approach can be too simplistic. These are important aspects to consider going forward.

4.6. Paper E: Using Model-based Systems Engineering to design human-centric manufacturing systems for novel products. A prescriptive case study, Part 2.

4.6.1. Purpose

The purpose of Paper E was to explore how systems engineering design support methods of *Model-based Systems Engineering* (INCOSE, 2015) can be used to reduce complexity and risk in the design of a new battery manufacturing system with a human-centric focus.

4.6.2. Results

To mitigate the challenges identified in the project, proposals of methods going forward were presented and Model-based Systems Engineering was selected. Results from earlier projects had shown that the focus from engineering had been more equipment-oriented than production system-oriented. In this project, even if the focus has been on equipment installations, there were still problems in production stemming from design. High-level Task clarification was developed from the Project goals, the Engineering goals, Goals break-down and Intended Impact Model as described in Figure 41, highlighting the focus for Paper D vs Paper E.

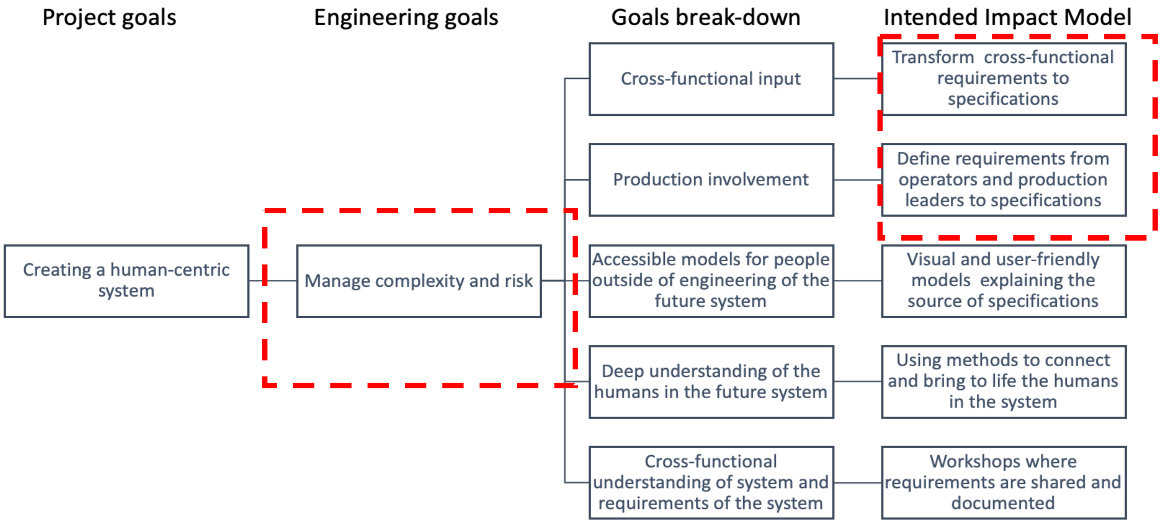
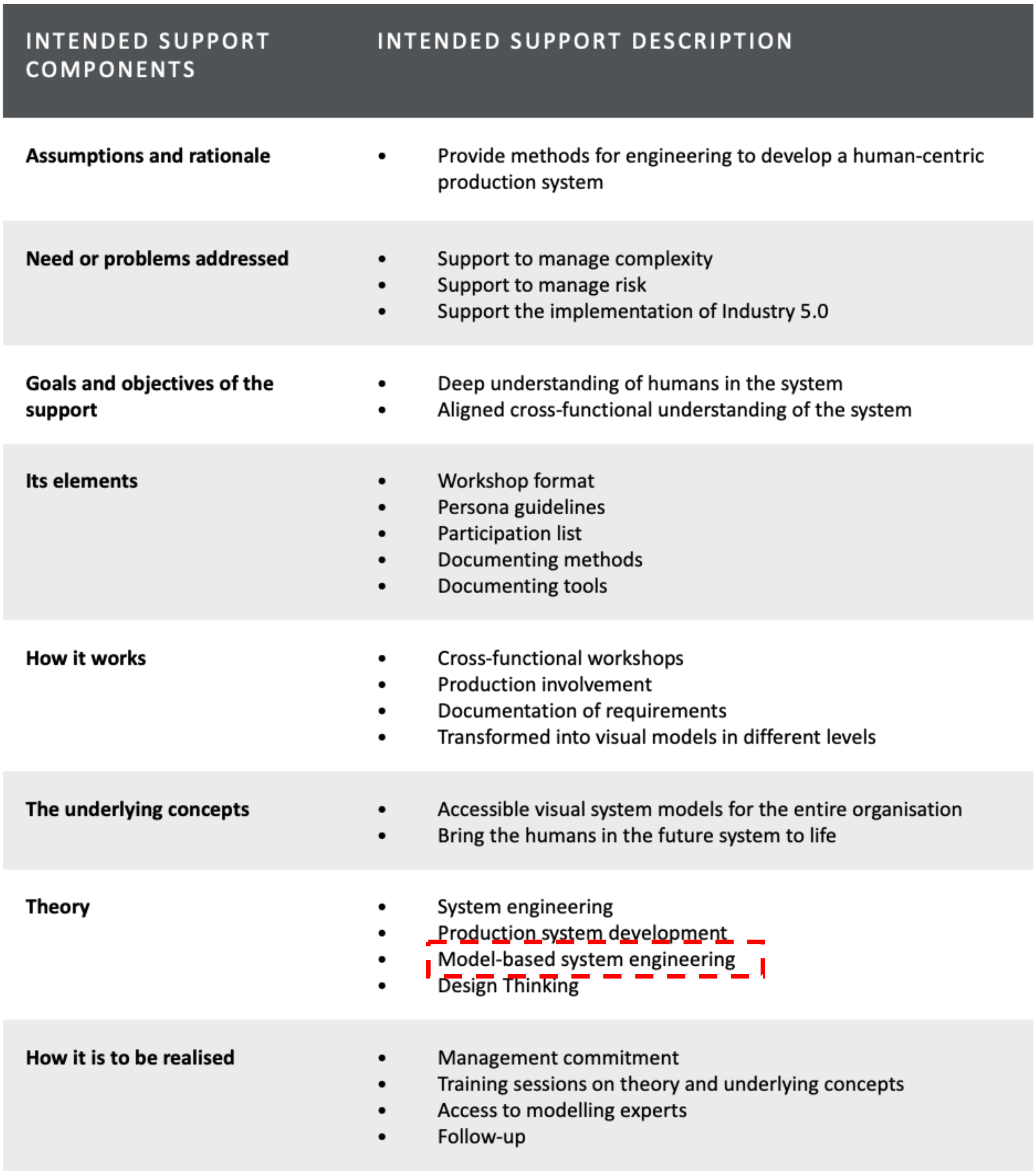


Figure 41: Logic of development of Intended Impact Model for the Comprehensive Predictive Study. The engineering goals were formulated differently in Paper D vs Paper E, and are highlighted to support the reader.

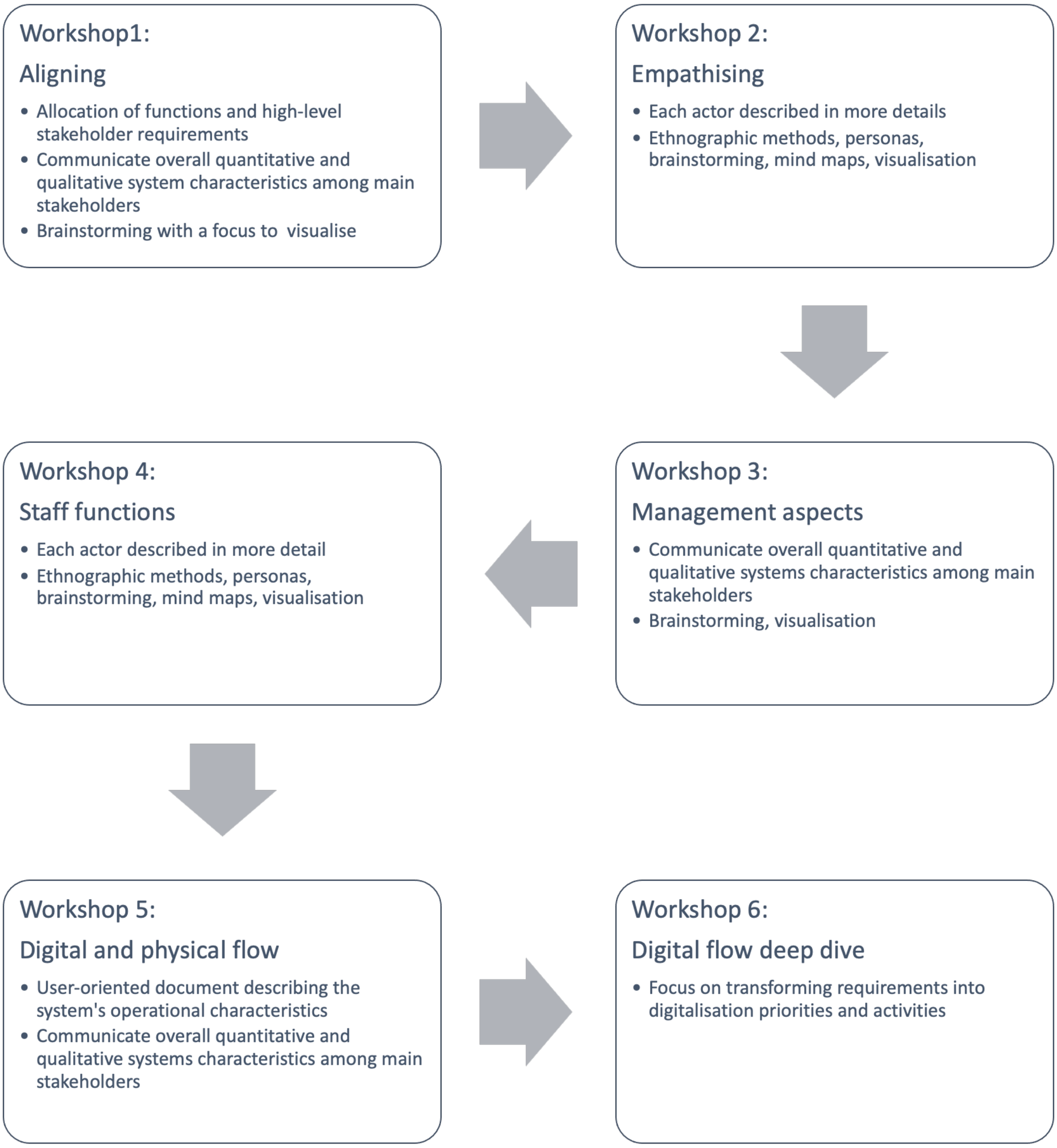
The Intended Support Description was generated from the task clarification documented in the Intended Impact Model. The Intended Support Description describes the support in terms of the need or problems addressed, the goals and objectives of the support, its elements, how it works, the underlying concepts, theory, assumptions and rationale, and how it is to be realised. The Intended Support Description is described in Table 11.

Table 11: Intended Support Description. The engineering goals were formulated differently in Paper D vs Paper E, and are highlighted to support the reader.



INTENDED SUPPORT COMPONENTS	INTENDED SUPPORT DESCRIPTION
Assumptions and rationale	• Provide methods for engineering to develop a human-centric production system
Need or problems addressed	• Support to manage complexity • Support to manage risk • Support the implementation of Industry 5.0
Goals and objectives of the support	• Deep understanding of humans in the system • Aligned cross-functional understanding of the system
Its elements	• Workshop format • Persona guidelines • Participation list • Documenting methods • Documenting tools
How it works	• Cross-functional workshops • Production involvement • Documentation of requirements • Transformed into visual models in different levels
The underlying concepts	• Accessible visual system models for the entire organisation • Bring the humans in the future system to life
Theory	• System engineering • Production system development • Model-based system engineering • Design Thinking
How it is to be realised	• Management commitment • Training sessions on theory and underlying concepts • Access to modelling experts • Follow-up

The sequence of the workshops as well as the set-up of each workshop were designed to collect data for both Paper D and Paper E simultaneously. The Intended Impact Model and Intended Support Description were iterated and an Intended Introduction Plan was generated, consisting of six workshops with various actors invited, as seen in Figure 42.



Workshop1:

Aligning

- Allocation of functions and high-level stakeholder requirements
- Communicate overall quantitative and qualitative system characteristics among main stakeholders
- Brainstorming with a focus to visualise

Workshop 2:

Empathising

- Each actor described in more details
- Ethnographic methods, personas, brainstorming, mind maps, visualisation

Workshop 3:

Management aspects

- Communicate overall quantitative and qualitative systems characteristics among main stakeholders
- Brainstorming, visualisation

Workshop 4:

Staff functions

- Each actor described in more detail
- Ethnographic methods, personas, brainstorming, mind maps, visualisation

Workshop 5:

Digital and physical flow

- User-oriented document describing the system's operational characteristics
- Communicate overall quantitative and qualitative systems characteristics among main stakeholders

Workshop 6:

Digital flow deep dive

- Focus on transforming requirements into digitalisation priorities and activities

Figure 42: Intended Introduction Plan consisting of six workshops with the aims of each workshop described (the same approach for Paper D and Paper E).

The workshops were designed to be three to four hours long and with the format described in Figure 43.

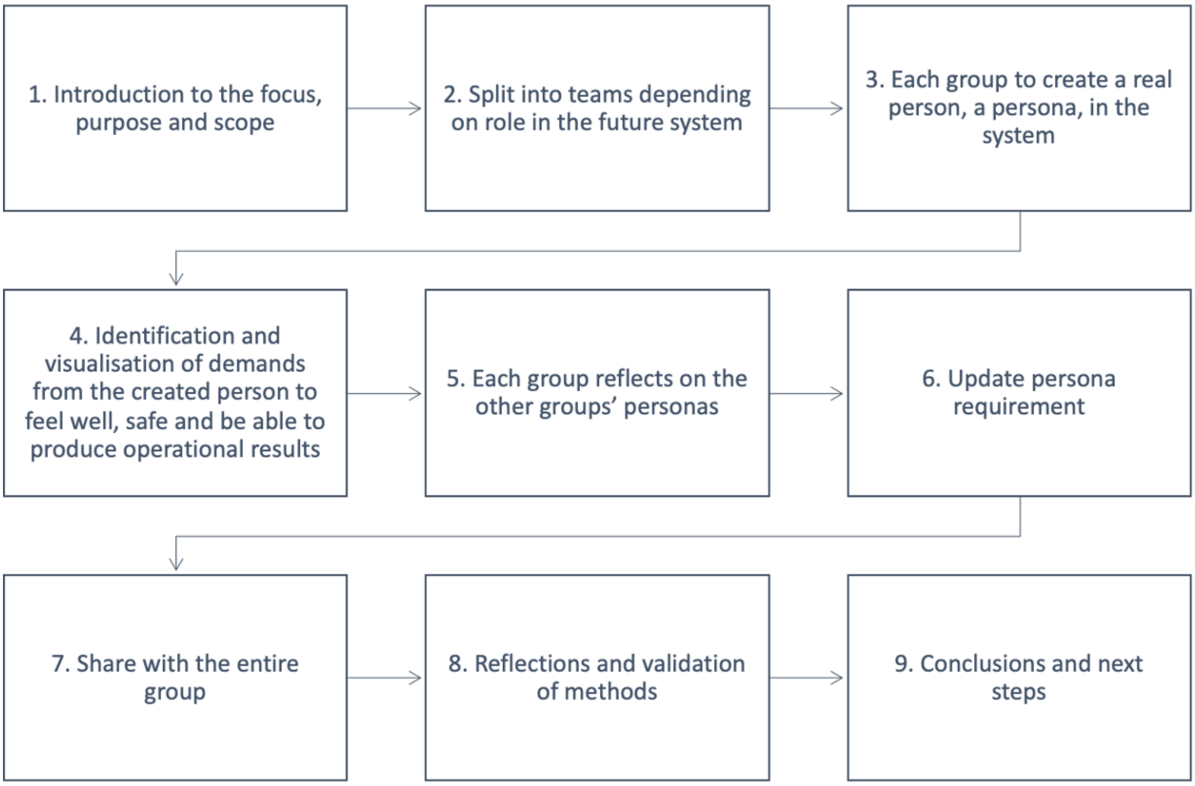


Figure 43: Workshop design for the six workshops (the same approach for Paper D and Paper E).

The focus of the Intended Design Support is to ensure how to get a satisfactory quality of input from all actors in the future system, hence the documentation and visualisation of the models were to be performed by the researchers and experts. In the realisation phase, the core functionalities of Intended Support, Actual Support developed and Actual Impact Model are elaborated on.

The participants documented the requirements in drawings in the workshops and the researchers documented them in the software, starting from the human in the production system. From the workshops, the requirements were organised in clusters and developed further within that category. The lines between some of the requirements indicate dependencies. The model is described in Figure 44.

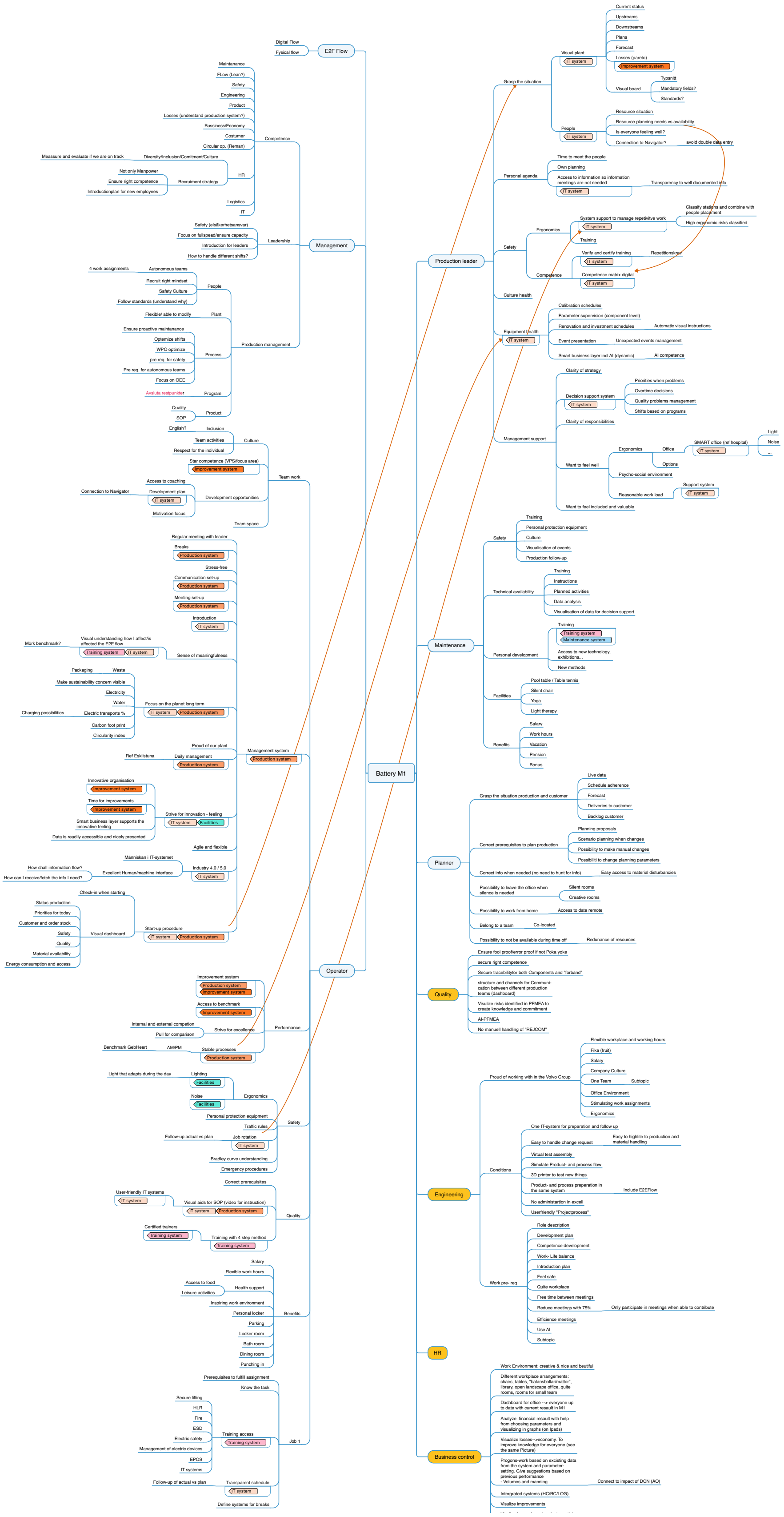


Figure 44: Model of the requirements identified in workshops, with the human in the system as the centre.

To be able to allocate to refine the demands and requirements further, the requirements were tagged by each sub-system by the project. Traditionally in projects like this, the demands are built up organisation by organisation; with this approach the project could identify requirements from an entire system view. The aim was to tag each requirement indicating which sub-system the requirement was influenced by. The sub-systems were Training system, IT system, Production System, Improvement system, Facilities system and Maintenance system. A zoom-in on the model is shown in Figure 45, with the tags for each requirement family.

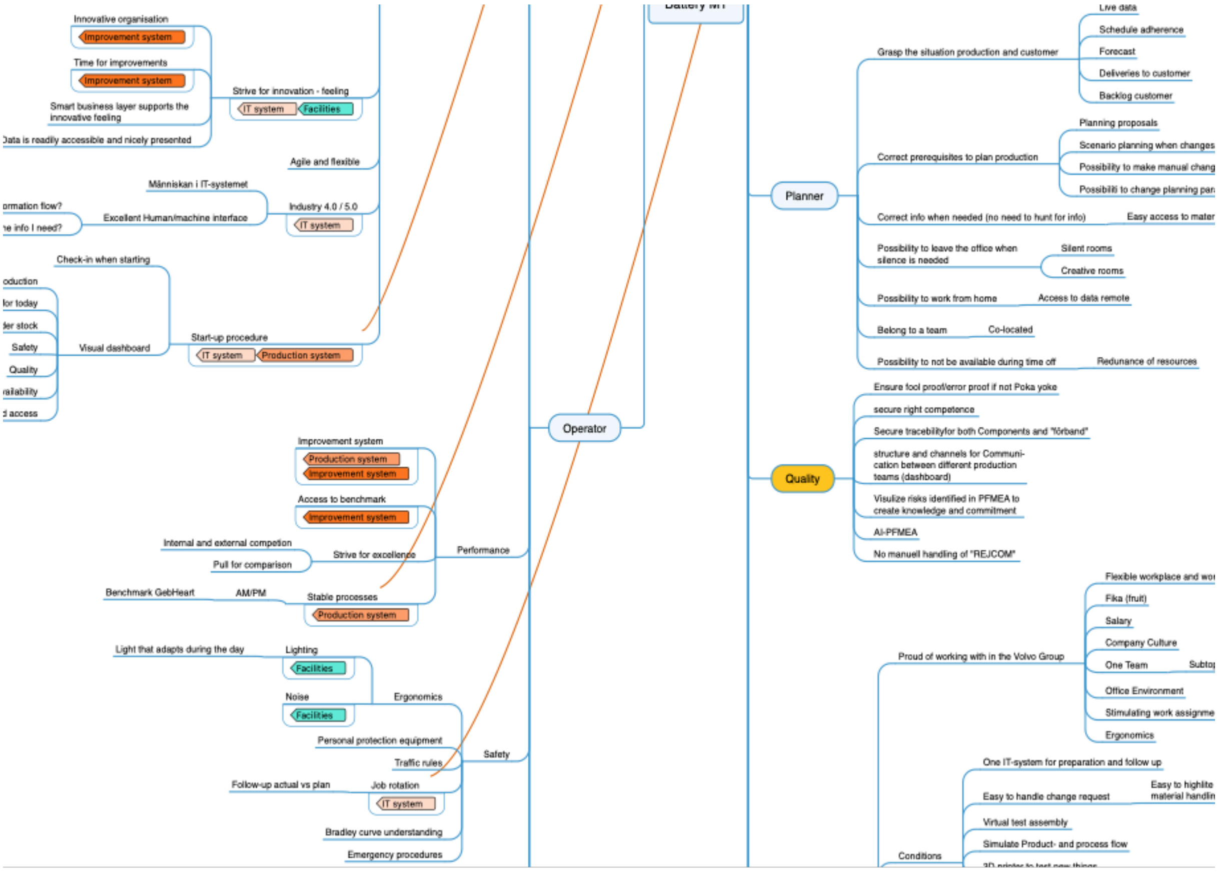
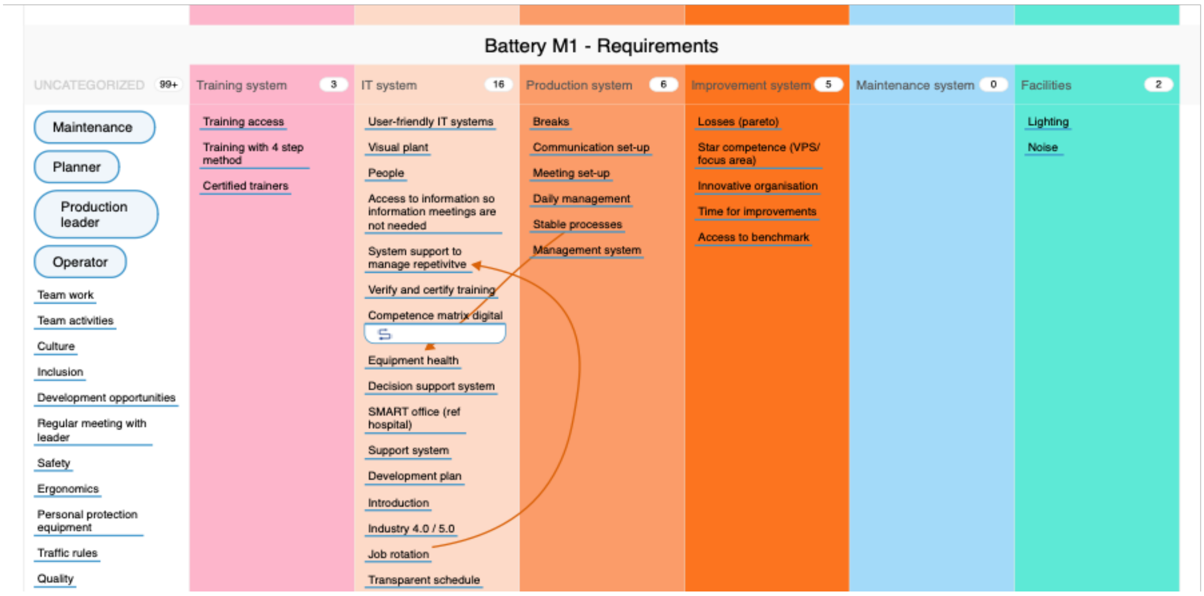


Figure 45: Zoom-in on requirement model with tags for each requirement or requirement family.

These tags are used to organise the requirements to the correct team, as seen in Figure 46.



Battery M1 - Requirements

UNCATEGORIZED 99+	Training system 3	IT system 16	Production system 6	Improvement system 5	Maintenance system 0	Facilities 2
Maintenance	Training access	User-friendly IT systems	Breaks	Losses (pareto)		Lighting
Planner	Training with 4 step method	Visual plant	Communication set-up	Star competence (VPS/ focus area)		Noise
Production leader	Certified trainers	People	Meeting set-up	Innovative organisation		
Operator		Access to information so information meetings are not needed	Daily management	Time for improvements		
Team work		System support to manage repetivtve	Stable processes	Access to benchmark		
Team activities		Verify and certify training	Management system			
Culture		Competence matrix digital				
Inclusion		Equipment health				
Development opportunities		Decision support system				
Regular meeting with leader		SMART office (ref hospital)				
Safety		Support system				
Ergonomics		Development plan				
Personal protection equipment		Introduction				
Traffic rules		Industry 4.0 / 5.0				
Quality		Job rotation				
		Transparent schedule				

Figure 46: Zoom in on requirement model tag view per sub-system (in progress of being developed).

From this exercise, 60 new demands from production to IT were identified and added to the work plan for the industrial project. The fulfilment by the Actual Design support to the Engineering goals are described in Table 12.

Table 12: Fulfilment by the Actual Design Support to the Engineering Goals

Engineering goal	Total	Yes	No	Confirming statement (selection)
Manage risk	26	26	-	• "It is clearer now that we are considering all aspects, it is very easy to miss the details." • "Great to listen to all perspectives and document every aspect". • "I realise how significant the logistics and planning will be". • "I realise that there are still many things we do not know." • "Really good input from the cross-functional teams. This helps us to get a wider perspective to see the bigger and end to end perspective". • "Easy to get stuck in your own silos so this is a way for this big project to get the holistic view", • "It has been a number of workshops; it really invites people to participate in the journey. I can see so many people from different areas, a lot of input for us in IT to work on"

The fulfilment by the Actual Design support to the Intended Impact Model are described in Table 13.

Table 13: Fulfilment by the Actual Design Support to Intended Impact Model

Intended Impact Model	Confirming statement (selection)
Transform cross-functional requirements to specifications	“Really good input from the cross-functional teams. This helps us to get a wider perspective to see the bigger and end to end perspective”
Define requirements from operators and production leaders to specifications	“Great that we all meet and see our faces, so many different projects that need to be combined”
Visual and user-friendly models explaining the source of specifications	“It is clearer now that we are considering all aspects, it is very easy to miss the details.”
Using methods to connect and bring to life the humans in the system	“It has been a number of workshops; it really invites people to participate in the journey. I can see so many people from different areas, a lot of input for us in IT to work on”
Workshops where requirements are shared and documented	“Great to listen to all perspectives and document every aspect”

4.6.3. Conclusions

The Design Support concept method to develop Concept of Operations was developed and delivered three artefacts on three levels of abstraction: the model of requirements from the human in the system, the categorisation of system requirements and the new 60 specifications towards IT. This approach addresses some of the problems identified in earlier studies in Paper A and Paper B, where system requirements were not developed in early stages, which could result in unnecessary equipment breakdowns and hence increased maintenance costs. This approach addressed issues identified in literature complementing the existing methods with new perspectives, which encouraged creativity and cross-functionality. The approach supported the transfer of knowledge within and between development teams. The approach supported the building of models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. This approach supported including humans in the systems right from the beginning, thus addressing the issue often seen in engineering of treating human aspects as an afterthought. Through this approach, several aspects were identified that had not been addressed, and work groups were set up to design solutions. The effectiveness of using this approach is difficult to assess completely as some of the expected effects, such as fewer problems (at least of in requirements) cannot be used as evidence until years later. However, it was possible to assess the participants’ immediate feedback and responses, e.g. regarding engagement. The main learning from the interviews with the workshop participants is that everyone felt that using these methods helps to manage risk. It was also appreciated as being more rigorous in terms of documentation than previous projects, as one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Some statements highlighted the importance of gaining an overview that was lacking before, and the importance of cross-functionality and collaboration.

4.7. Paper F: A Proposed Framework Using Systems Engineering To Design Human-Centric Manufacturing Systems For Novel Products To Reduce Complexity And Risk

4.7.1. Purpose

The purpose of Paper F was to propose a framework based on system engineering for the production system engineering community. The task of the framework has been clarified on the basis of a literature review, the previous case studies and the problem statement, which is defined as "Develop a systematic and effective framework to help experienced manufacturing engineers to take into consideration human-centric factors when designing production systems for novel products". From this, a requirements list was drawn up explaining what the framework should contribute. The list has since been conceptualised. The framework was selected for development in accordance with the ISO/IEC/IEEE 15288 standard using a Concept of Operations and Model-based Systems Engineering in a workshop setting, with a focus on visualisation, understanding the practical and emotional needs of the client and using prototypes or physical models.

4.7.2. Results

Earlier literature review from Paper C has identified two barriers concerning the extent to which the production system design community has adopted system engineering methods to take into consideration human-centric factors:

- Lack of systematic and effective system engineering design methods in production system design with the main barriers being: a) A failure to address the challenge of transferring the vast amount of knowledge within and between development teams, b) Difficulty in retrieving knowledge from previous projects, c) Models that are not clearly understood by designers, d) Ambiguity regarding the responsibilities involved in each task because of a lack of commitment on the part of functional departments and e) Methods that do not encourage creativity
- Failure to include human factors in the production system design

Papers D and E identified that the focus of the engineering department was:

- More equipment-oriented than production system-oriented
- More equipment-oriented than human-centric

Of the gaps identified in previous studies, nine were targeted to be addressed as described in the intended impact model of the developed framework in Table 14.

Table 14: Intended impact model of the developed framework

Problem statement: Develop a systematic and effective framework to help experienced manufacturing engineers take into consideration human-centric factors when designing production systems for novel products.	
Requirement list:	
	System view
R1	The framework should help to manage complexity
R2	The framework should help to manage risk

R3	The framework should offer a systematic and effective system engineering design method for use in production system design
R4	The framework should focus on the system, not only the equipment
	Human-centricity
R5	The framework should help to include the human factors, alongside the focus on the equipment
	Design methods
R6	The framework should help to develop designers' abilities
R7	The framework should address the transfer of knowledge within and between development teams
R8	The framework should support models that are clearly understood by designers
R9	The framework should encourage creativity

On the basis of the requirements developed in the intended impact model, the main functions of the framework are described in Table 15.

Table 15: Main functions based on the intended impact model of the developed framework

Requirement list:	
	Main function
	System view
R1	Visualisation of the system overview to give a collective understanding of what the system will do. This allows complexity to be understood by all parties in the project
R2	Visualisation of the system overview to give a collective understanding of what the system will do. This enables the main risks to be identified by all parties in the project
R3	A usable concept for the engineers' working methods when designing human-centric manufacturing systems for novel products to reduce complexity and risk
R4	Visualisation of the system overview to give a collective understanding of what the system will do. This allows the equipment to be seen in a context and enables decisions to be taken based on a system view
	Human-centricity
R5	Understanding the practical and emotional needs of a person in the system, using prototypes or physical models to explore possible ways of achieving goals
	Design methods
R6	Sufficiently instructive to enable engineers to increase their competence
R7	Using models that can be understood by other functional teams
R8	Using models that can be understood by the designers within the team
R9	Creativity is encouraged in the different ways of working

On the basis of the results of earlier case studies, the framework is selected to be developed in accordance with the ISO/IEC/IEEE 15288 (2023) standard using the Concept of Operations and Model-based Systems Engineering in a workshop setting, with a focus on visualisation, understanding the practical and emotional needs of a client and using prototypes or physical models. These findings were identified in collaboration with the engineers and cross-functional teams. The aim was to create a high-level requirements specification at an early stage for the generation of potential solutions. Based on the teams' evaluations, it would then be possible to generate solution-specific requirements. The combination of earlier studies allowed the problem statement to be generated and this was broken down into the main functions. A framework was then developed, which is shown in Figure 47.

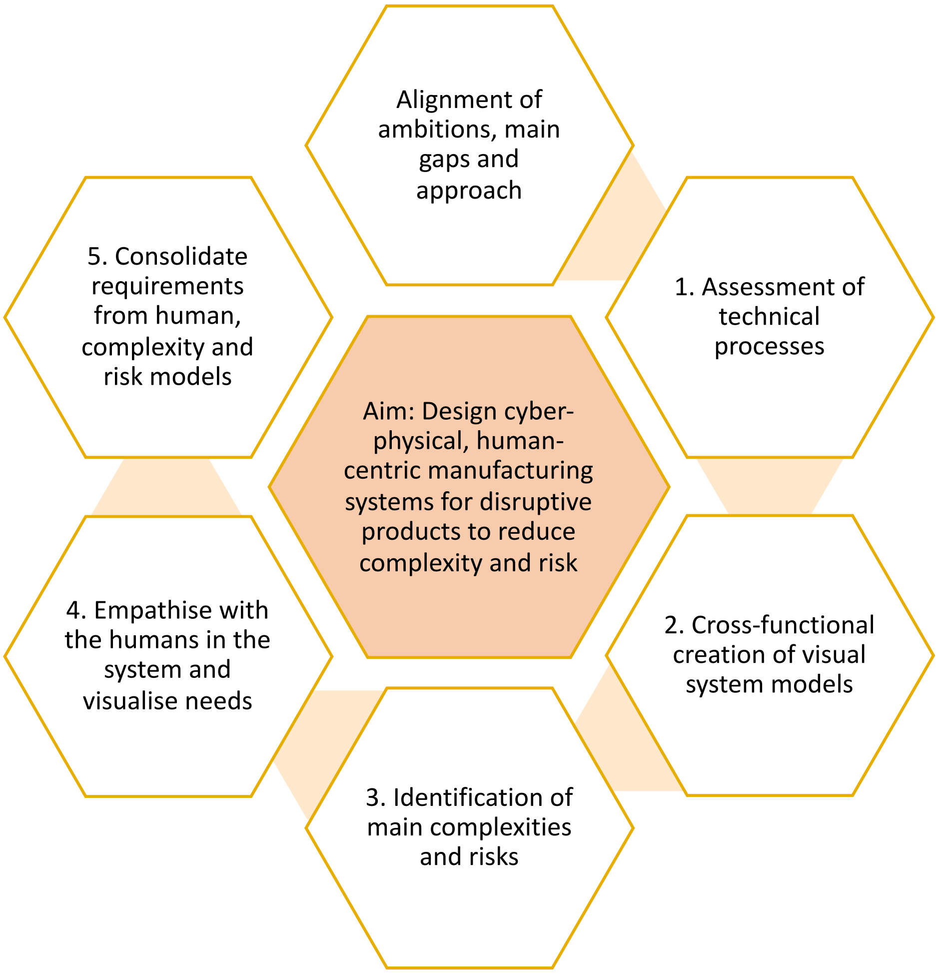


Figure 47: Proposed system engineering framework for the design of human-centric manufacturing systems for novel products to reduce complexity and risk

The initial alignment of the aims, main gaps and approach is crucial for the success of any project, but this is not developed further in this paper. The intended support description for each stage is given in Table 16.

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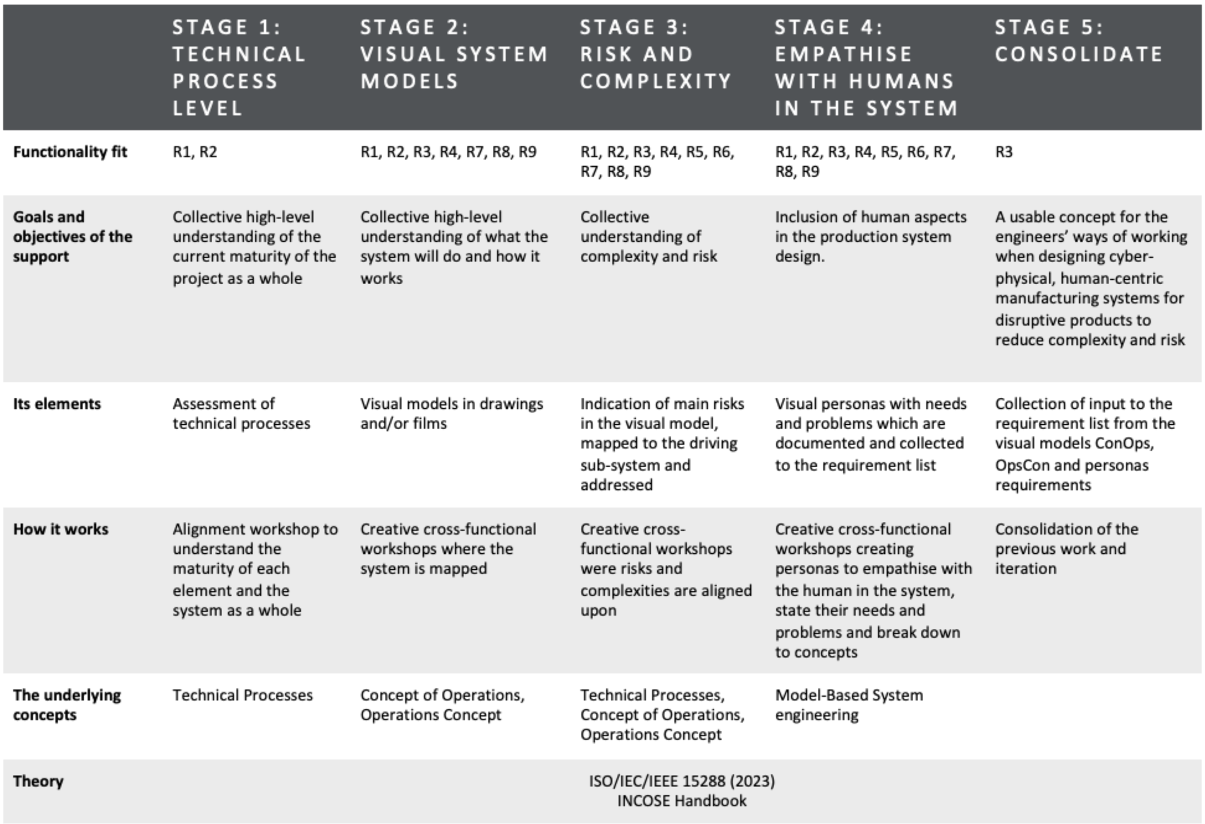
Table 16: Intended support description for each stage of the developed framework



	STAGE 1: TECHNICAL PROCESS LEVEL	STAGE 2: VISUAL SYSTEM MODELS	STAGE 3: RISK AND COMPLEXITY	STAGE 4: EMPATHISE WITH HUMANS IN THE SYSTEM	STAGE 5: CONSOLIDATE
Functionality fit	R1, R2	R1, R2, R3, R4, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R3
Goals and objectives of the support	Collective high-level understanding of the current maturity of the project as a whole	Collective high-level understanding of what the system will do and how it works	Collective understanding of complexity and risk	Inclusion of human aspects in the production system design.	A usable concept for the engineers' ways of working when designing cyber-physical, human-centric manufacturing systems for disruptive products to reduce complexity and risk
Its elements	Assessment of technical processes	Visual models in drawings and/or films	Indication of main risks in the visual model, mapped to the driving sub-system and addressed	Visual personas with needs and problems which are documented and collected to the requirement list	Collection of input to the requirement list from the visual models ConOps, OpsCon and personas requirements
How it works	Alignment workshop to understand the maturity of each element and the system as a whole	Creative cross-functional workshops where the system is mapped	Creative cross-functional workshops were risks and complexities are aligned upon	Creative cross-functional workshops creating personas to empathise with the human in the system, state their needs and problems and break down to concepts	Consolidation of the previous work and iteration
The underlying concepts	Technical Processes	Concept of Operations, Operations Concept	Technical Processes, Concept of Operations, Operations Concept	Model-Based System engineering	
Theory			ISO/IEC/IEEE 15288 (2023) INCOSE Handbook		

The proposed framework has been tested with validation follow-up in the case studies in Part 1 and Part 2 of this series of papers. The framework was also validated in a workshop covering Stage 1 to Stage 4 with the battery cell plant management team, a total of twelve cross-functional managers. All the participants answered yes to the questions regarding support. Some of the comments concerning the management of complexity included: “The early visualisation helps you structure the work and ask yourself the right questions”, “It was a good way to get an overview of the process and start discussing complexities When we are all looking at the same picture”, “The complexity becomes tangible when we as a team describe what we want to achieve”, “We were all able to brainstorm together and assess the same issue/situation from different points of view”, “Pictures are always easier to relate to and team discussions provide leverage”, “Yes, everybody contributing and being part of the discussion creates a structure in itself”, “This gets us all aligned and helps us to learn. When things are moving quickly in all areas, the need for these kinds of workshops increases to help us manage complexity”.

Some of the comments about the management of risks were: “The early visualisation forces us to align and that means we can mitigate many of the risks”, “Breaking down the questions and putting the focus on a person in the work environment makes it easier to understand the risks with the focus on the human aspects”, “Expressing the complexity and putting it into words helps you understand the risk”, “We were able to share all our previous experiences of failure related to running a plant in the operations team. We also discussed measures we could take to overcome the problems”, “Yes, we can identify the risks early – the earlier the better”, “It helps us understand the different areas and identify things we haven’t addressed”.

On the subject of the implementation of Industry 5.0, a concept defined by the company, the comments were: “The visualisation helps you to solve the obvious issues, but the environmental and human dimensions help you to move from Industry 4.0 to Industry 5.0”, “This method brings up questions during team discussions and it creates possibilities for discussing complex issues”, “This is a good start but I need to understand and refine Industry 5.0 in more detail, so that we can make it more understandable and easier to implement", "Yes, we were trying to think about solutions not only in the traditional ways, but also considering new technologies such as AI", "Yes, this gives you a fairly clear method for addressing different dimensions of the concept", "By bundling our vision across three relevant perspectives, we can create a base for our overall storyline and employer branding so that we can attract young people and professionals in mid-career to the industry and to our company".

4.7.3. Conclusions

The framework combines several system engineering methods for designing manufacturing systems for novel products to reduce complexity and risk. The framework proposes a combination of systematic design methods and cross-functional creativity with visual system models. It targets the early stages of a project: the specification and concept development phase. Studies in the case company showed that the developed framework had produced promising results, both by identifying new requirements and by using feedback from interviews with the project members about the way of working. By combining the system engineering methods of technical process assessment, Concept of Operations, Operations Concept, Design Thinking and Model-based Systems Engineering, the framework has placed new demands on IT that had not been identified in the traditional models used by the case company. The framework has also received promising feedback from validation workshops with a total of 134 people: twelve people for this paper and 122 people for Part 1 and Part 2. When investigating the extent to which the production system design community has adopted system engineering methods to take into consideration human-centric factors, the main issues identified in the literature reviews from the previous case studies revolve around two gaps: 1) A lack of systematic and effective system engineering design methods in production system design and 2) A failure to include human factors in production system design. The framework can address these issues as it proposes a systematic system engineering design method for use in production system design which supports the inclusion of human factors. However, the problems with the effectiveness of the methods have not yet been evaluated, as the project still has a few more years to run. Further research is proposed that will focus on the implementation of frameworks in system engineering design methods in production system design, in particular for novel products, where a large amount of new knowledge needs to be developed. In addition, further research on the integration of human factors into production system engineering design is required to prepare for future generations of workers. Finally, there is a need to explore further how the production system design engineering community can learn from the product development community and to identify whether these methods would have any actual impact on project cost and lead time overruns, the workload of engineers and better production systems in terms of resilience, sustainability and human factors.

5. Synthesis

This chapter presents the synthesis of the work. It presents the identified research gaps, the developed Design Support framework Visual Design Human Centric Production (VDHCP), the stages in the framework, how the model addresses the research gaps and a summary

5.1. Identified research gaps

As presented in Chapter 1, the research gaps are identified as:

- Research gap 1 (RG1): Lack of systematic and effective systems engineering design methods in production system design.
- Research gap 2 (RG2): Lack of inclusion of human aspects in the production system design.

The research gaps are further elaborated on in Chapter 2 and summarised. An extract from the main references with only the sources reflecting the research gaps is presented in Table 17.

Table 17: Extract of main references corresponding to Research Gap 1 and Research Gap 2

Topic	**Main references**	**Main takeaways**	**Research gaps**
Concept of Operations	(Fairley & Thayer, 1997) (Madni & Orellana, 2018) (Kaasinen et al., 2022)	“ConOps/OpsCon documents have been developed in many domains, such as the military, health care, traffic control, space exploration and financial services, as well as various industries such as nuclear power, pharmaceuticals and medicine, but not much in production system design” (author comment)	RG1
Model-Based Systems Engineering	(Beydeda et al., 2005) (Madni & Purohit, 2019) (Berschik, 2023)	“A literature review performed by Berschik et al (2023) on the usage of MBSE in the engineering design community showed that of 56 papers that were selected for analysis, only three of them addressed the linkage of system and production. (Berschik, 2023)”	RG1
		“A study in the case company by Hane Hagström et al (2022) showed that production system engineers are using a total of 46 different document types only for equipment acquisition projects, with none of them being model-based but drawings or test”.	RG1
Human centric systems engineering	(Madni & Orellana, 2018) (Handley & Smillie, 2008) (Patrick Neumann & Dul, 2010)	“The human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk (Handley & Smillie, 2008)”	RG2
		“According to Neumann and Du (2010), the careful consideration of the human being in the design can improve productivity, quality and technology implementation, and can have intangible benefits for operations while also improving worker well-being and working conditions.”	RG2
		“In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practises tend to address human considerations as an afterthought” (Madni & Orellana, 2018)	RG2
Production systems design capabilities	(Islam et al., 2020) (Vielhaber & Stoffels, 2014) (Hane Hagström et al., 2022) (Arista et al., 2023) Stark et al. (2017)	“There is still a lack of empricial studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap” (Islam et al., 2020).	RG1
		“Vielhaber and Stoffels identified that in academia there is a larger focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts” (Vielhaber & Stoffels, 2014).	RG1
		“When focusing on maintenance cost as one indicator of the production system design capabilities, maintenance costs grow in the early life of a machine, which is not the aim; that new equipment has higher maintenance costs than old machines nearing their end of life; and that design errors account for about 20-25% of the reasons behind unplanned machine downtime” (Hane Hagström et al., 2022)	RG1
		“only parts of the design process knowledge are captured explicitly using different documentation approaches and very little information persists from one design to another. Designers take decisions based on their assessment and experience (Arista et al., 2023)	RG1
		Today’s manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity” . “In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity”. Stark et al. (2017)	RG1

5.2. Workshop design

The workshops are described in terms of number of participants, theme, organisations represented, organisational hierarchy and the output from each workshop. In total for Paper D, E and F, 178 participants were present, although many of the individuals joined multiple workshops. Table 18 summarises the workshops held with the number of participants, theme of each workshop, organisations represented and organisational hierarchy.

Table 18: Summary of workshops held with number of participants, theme of each workshop, organisations represented, organisational hierarchy and output from workshop.

Workshop #	*Theme*	*Organisations represented*	*Organisational hierarchy*	*Output from workshop*
1 *(22 p.)*	Alignment reference group	Production, Logistics, Engineering, Logistics Engineering, Maintenance, Planning, IT	Sr leadership, middle management, project members	Co-created and shared visual models of alignment in requirements from the system
2 *(44 p)*	Empathising with the people in the system	Production, Logistics, Engineering, Logistics engineering, Maintenance, Planning, IT, operators, maintenance technicians, circular operations	Sr leadership, middle management, project members, operators	Co-created and shared visual models of six personas identified with their requirements on the future system
3 *(22 p)*	Management aspects of preparing, ramping up and running production	Production, Logistics, Engineering, Logistics engineering, Maintenance, Planning, IT	Middle management, project members	Co-created and shared three descriptions on the most important aspects from management
4 *(28 p)*	Staff functions, humans in the system	Quality, engineering, maintenance, logistics	Middle management, project members	Co-created and shared five personas identified with their requirements on the future system
5 *(38 p)*	Digital and physical flow	Customers and suppliers in the end-to end flow, Production, Logistics, Engineering, Logistics Engineering, Maintenance, Planning, IT	Middle management, project members	Co-created and shared visual models of the main risks in the end-to-end digital and physical flow
6 *(12 p)*	Digital flow deep dive	Production, IT, Engineering	Middle management, operators	60 new demands from production to IT

5.3. The developed Design Support framework Visual Design Human Centric Production (VDHCP)

The work presented in this thesis aims to address RG1 and RG2 via the Visual Design Human Centric Production (VDHCP) framework; a design support developed for Production System Engineering when designing cyber-physical, human-centric production systems for novel products to reduce complexity and risk. VDHCP is described in Figure 48.

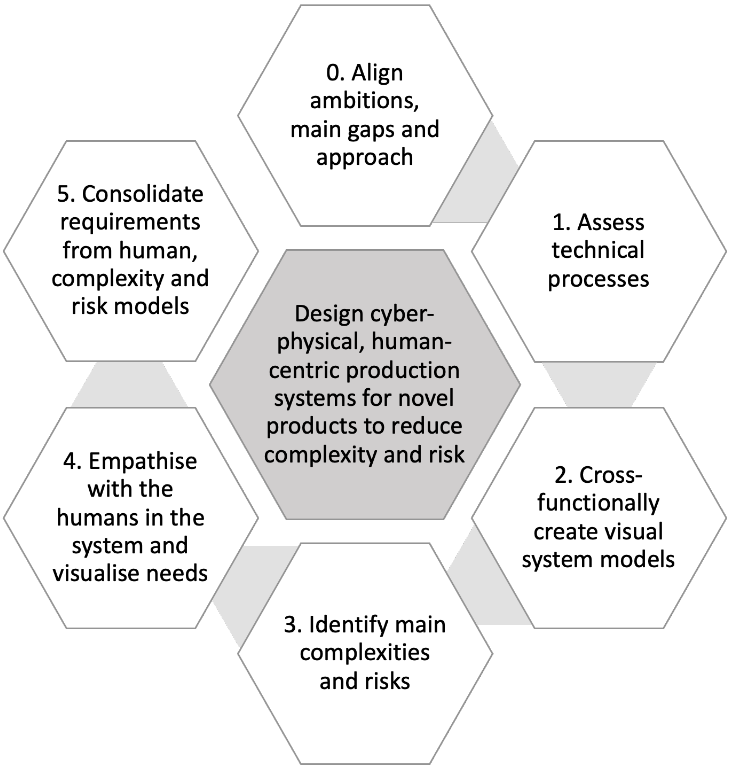


Figure 48: Visualisation of the framework Visual Design Human Centric Production (VDHCP) as a Design Support to Production System Engineering with the aim to design cyber-physical, human-centric production systems for novel products to reduce complexity and risk

5.4. The stages in the framework Design Support framework Visual Design Human Centric Production (VDHCP)

The steps in the VDHCP model are further elaborated on in Table 19.

Table 19: The steps in the developed design support framework Visual Design Human Centric Production (VDHCP) for Production System Engineering with the aim to design cyber-physical, human-centric production systems for novel products to reduce complexity and risk

	Stage 1: Assess technical process	**Stage 2: Create visual system models**	**Stage 3: Identify complexity and risk**	**Stage 4: Empathise with humans in the system**	**Stage 5: Consolidate**
Functionality fit	R1, R2	R1, R2, R3, R4, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R1, R2, R3, R4, R5, R6, R7, R8, R9	R3
Goals and objectives of the support	Collective high-level understanding of the current maturity of the project as a whole	Collective high-level understanding of what the system will do and how it works	Collective understanding of complexity and risk	Inclusion of human aspects in the production system design.	A usable concept for the engineers' ways of working when designing cyber-physical, human-centric manufacturing systems for disruptive products to reduce complexity and risk
Its elements	Assessment of technical processes	Visual models in drawings and/or films	Indication of main risks in the visual model, mapped to the driving sub-system and addressed	Visual personas with needs and problems which are documented and collected to the requirement list	Collection of input to the requirement list from the visual models ConOps, OpsCon and personas requirements
How it works	Alignment workshop to understand the maturity of each element and the system as a whole	Creative cross-functional workshops where the system is mapped	Creative cross-functional workshops where risks and complexities are aligned upon	Creative cross-functional workshops creating personas to empathise with the human in the system, state their needs and problems and break down to concepts	Consolidation of the previous work and iteration
The underlying concepts	Technical Processes	Concept of Operations, Operations Concept	Technical Processes, Concept of Operations, Operations Concept	Model-Based System engineering Design thinking	Out of scope
Theory	ISO/IEC/IEEE 15288 2023 INCOSE Handbook, 2020	Fairley & Thayer, 1997 Madni & Orellana, 2018 Kaasinen et al., 2022	Blanchard & Fabrycky, 1998) Stevens, 1998 INCOSE, 2015	Beydeda et al., 2005 Madni & Purohit, 2019 Cross, 1984 Rowe, 1991 Purdy & Popan, 2023 Micheli et al., 2019	Out of scope

5.5. How the framework Design Support framework Visual Design Human Centric Production (VDHCP) addresses the research gaps

The VDHCP framework addresses the identified research gaps according to Table 20.

Table 20: Mapping VDHCP to the identified research gaps 1 and 2 and at which stage the gap is addressed.

Topic	**Main references**	**Main takeaways**	**Research gaps**	**VDHCP**
Concept of Operations	(Fairley & Thayer, 1997) (Madni & Orellana, 2018) (Kaasinen et al., 2022)	"ConOps/OpsCon documents have been developed in many domains, such as the military, health care, traffic control, space exploration and financial services, as well as various industries such as nuclear power, pharmaceuticals and medicine, but not much in production system design" (author comment)	RG1	Stage 2
Model-Based Systems Engineering	(Beydeda et al., 2005) (Madni & Purohit, 2019) (Berschik, 2023)	"A literature review performed by Berschik et al (2023) on the usage of MBSE in the engineering design community showed that of 56 papers that were selected for analysis, only three of them addressed the linkage of system and production. (Berschik, 2023)"	RG1	VDHCP
		"A study in the case company by Hane Hagström et al (2022) showed that production system engineers are using a total of 46 different document types only for equipment acquisition projects, with none of them being model-based but drawings or test".	RG1	Stage 4
Human centric systems engineering	(Madni & Orellana, 2018) (Handley & Smillie, 2008) (Patrick Neumann & Dul, 2010)	"The human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk (Handley & Smillie, 2008)"	RG2	Stage 4
		"According to Neumann and Du (2010), the careful consideration of the human being in the design can improve productivity, quality and technology implementation, and can have intangible benefits for operations while also improving worker well-being and working conditions."	RG2	Stage 4
		"In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practises tend to address human considerations as an afterthought" (Madni & Orellana, 2018)	RG2	Stage 4
Production systems design capabilities	(Islam et al., 2020) (Vielhaber & Stoffels, 2014) (Hane Hagström et al., 2022) (Arista et al., 2023) Stark et al. (2017)	"There is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap" (Islam et al., 2020).	RG1	VDHCP
		"Vielhaber and Stoffels identified that in academia there is a larger focus on product development than on production development. In particular, methodologies and process models dedicated to production equipment have lower scientific coverage than their product-oriented counterparts" (Vielhaber & Stoffels, 2014).	RG1	
		"When focusing on maintenance cost as one indicator of the production system design capabilities, maintenance costs grow in the early life of a machine, which is not the aim; that new equipment has higher maintenance costs than old machines nearing their end of life; and that design errors account for about 20-25% of the reasons behind unplanned machine downtime" (Hane Hagström et al., 2022)	RG1	
		"only parts of the design process knowledge are captured explicitly using different documentation approaches and very little information persists from one design to another. Designers take decisions based on their assessment and experience (Arista et al., 2023)	RG1	VDHCP
		Today's manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity" . "In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (...) without any true systems engineering design opportunity". Stark et al. (2017)	RG1	VDHCP

5.6. Visual Design Human Centric Production (VDHCP) summary

Visual Design Human Centric Production (VDHCP) framework combines system engineering methods for designing human-centric manufacturing systems for novel products to reduce complexity and risk. The framework consists of a combination of the system engineering methods of technical process assessment, Concept of Operations, Operations Concept, Design Thinking and Model-based Systems Engineering. VDHCP targets the early stages of a project: the specification and concept development phase. Studies in the case company show that the developed framework has produced promising results, both by identifying 60 new IT requirements and by using feedback from interviews with the project members about the way of working. These new demands had not been identified in the traditional models used by the case company. The framework, either parts or the entire framework, has received promising feedback from validation workshops with a total of 178 people, where many individuals joined multiple workshops.

6. Discussion

In this chapter, the research questions are further evaluated. The research questions are reflected on in an attempt to answer them. Validation of research gaps, industrial problems and design method are discussed.

6.1. Answers to RQ1: What is the current systems engineering state of practice in designing human-centric production systems?

The answer to RQ1 is mainly derived from Paper A, Paper B and Paper C. RQ1 addresses the question from the Research Gaps 1 and 2 as identified from literature, and from industry case studies. The literature review is further developed in Chapter 2. The main issues identified in the literature review and the two case studies revolve around two research gaps:

- RG1: Lack of systematic and effective systems engineering design methods in production system design (Vielhaber & Stoffels, 2014), (Islam et al., 2020) (Arista et al., 2023), (Stark et al. (2017) (Berschik, 2023), (Hane Hagström et al., 2022), (Hagström et al., 2020)
- RG2: Lack of inclusion of human aspects in the production system design (Handley & Smillie, 2008), (Patrick Neumann & Dul, 2010), (Madni & Orellana, 2018)

Regarding the first gap, there are several challenges that concern product development in general, including production system design, such as the lack of systematic methods, that designers' abilities are not developed enough, that the methods do not encourage creativity, and that there are less systematic ways to objectively evaluate the results. Focusing on current state of practice for production system design, literature identifies further issues, such as that process models dedicated to production development have lower scientific coverage than their product-oriented counterparts, that production system designers take decisions based on their assessment and experience rather than true systems engineering design, that only parts of the design process knowledge are captured explicitly using different documentation approaches, and that very little information persists from one design to another and limited usage of Model-based Systems Engineering in production system design. The case studies have shown that production equipment losses due to production system design weaknesses is increasing and that production system engineers mainly use text documents or drawings for equipment acquisition projects, with less use being made of models or Model-based Systems Engineering.

The second gap regards the lack of inclusion of human aspects in production system design. The literature can be summarised as tending towards over-simplification when describing model-based design, thus disregarding individual personality and skill profiles, since in complex systems, humans are often part of the complex system rather than simply users of the system. Engineering practices tend to address human considerations as an afterthought. In this regard, the literature identifies a failure of the engineering community to adequately present the value proposition of human system integration, where the human is the most important and unique element in a system, as well as the weakest link and potentially the highest risk factor.

6.2. Answers to RQ2: How can the systems engineering methods of Concept of Operations and Operational Concept be used to reduce complexity and risk in the design of a human-centric production system for novel products?

The answer to RQ2 is mainly derived from Paper D.

The Design Support concept method to develop Concept of Operations was developed and delivered three artefacts on three levels of abstraction. This approach addressed issues identified in literature that complement the existing methods with new perspectives which encouraged creativity and cross-functionality. The approach supported the transfer of knowledge within and between development teams. The approach provided support in building models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. This approach supported the inclusion of humans in the systems right from the beginning, thus addressing the issue often seen in engineering of treating human aspects as an afterthought. Through this approach, several aspects were identified that had not previously been identified or considered which are more system-oriented, such as flows between different equipment, how to access the plant easily, and digital communication between equipment and humans. These topics were now addressed, and work groups were set up to design solutions. However, it has not yet been possible to identify the gaps in the effectiveness of the methods as the project will still be running for a few more years.

The main learning from the interviews with the workshop participants is that all except one person thought that using these methods helps to manage complexity. It was also appreciated as being more rigorous in terms of documentation than previous projects, since one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Regarding the management of risks, the input was equally supportive. For instance, it was stated that this method helps to identify and mitigate risks early in the project. Participants mentioned the importance of gaining an overview that they had previously lacked, and the importance of cross-functionality, collaboration and flow thinking supports this finding. It was also stated that with this approach, concepts can be developed more precisely and demands become more tangible. Some participants said that it takes some effort to understand the methods, but that using a more intuitive approach can be too simplistic. These are important aspects to consider going forward.

6.3. Answers to RQ3: How can the systems engineering methods of Model-based Systems Engineering be used to reduce complexity and risk in the design of human-centric production system for novel products?

The answer to RQ3 is mainly derived from Paper E.

The Design Support concept method to develop Model-based Systems Engineering was developed and delivered three artefacts on three levels of abstraction: the model of requirements from the human in the system, and the new 60 specifications towards IT. This approach addressed issues identified in literature complementing the existing methods with new perspectives, which encouraged creativity and cross-functionality. The approach supported the transfer of knowledge within and between development teams. The approach supported the building of models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. This approach supported including humans in the systems right from the beginning, thus addressing the issue often seen in engineering of treating human aspects as an afterthought. Through this approach, several aspects were identified that had not been addressed, and work groups were set up to design solutions. However, the gaps in the effectiveness in the methods could not yet be evaluated as the project will still be running for a few more years.

The main learning from the interviews with the workshop participants is that everyone thought that using these methods helps to manage risk. It was also appreciated as being more rigorous in terms of documentation than previous projects, as one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Statements regarding the importance to get the overview that they were missing before, and the importance of cross-functionality and collaboration.

6.4. Answers to RQ4: How could a systems engineering framework to design human-centric production systems for novel products to manage risk and complexity be designed?

The answer to RQ4 is mainly derived from Paper D, Paper E and Paper F.

From Paper D, the main learning is that all except one person thought that using these methods helps to manage complexity as a visual model is created cross-functionally. It was also appreciated as being more rigorous in terms of documentation than previous projects, since one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Regarding the management of risks, the input was equally supportive, stating that this method helps to identify and mitigate risks early in the project. Participants mentioned the importance of gaining an overview that they had previously lacked, and the importance of cross-functionality, collaboration and flow thinking supports this finding. It was also stated that with this approach, concepts can be developed more precisely and demands become more tangible. Some participants said that it takes some effort to understand the methods, but that using a more intuitive approach can be too simplistic. These are important aspects to consider going forward.

From Paper E the main learnings are that everyone thought that using these methods is helping to manage risk. It was also appreciated to be more rigorous in the documentation than previous projects, as one focus of the workshops was to document the concepts selected and develop a system concept of the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Statements regarding the importance to get the overview that they were missing before, and the importance of cross-functionality and collaboration.

The framework in Paper F, Visual Design for Human Centric Production (VDHCP) combines system engineering methods for designing human-centric manufacturing systems for novel products to reduce complexity and risk. The framework proposes a combination of systematic design methods of Concept of Operations, Model-based Systems Engineering with cross-functional creativity with visual system models. It targets the early stages of a project: the specification and concept development phase. Studies within the case company showed that the developed framework had produced promising results, both by identifying new requirements and by using feedback from interviews with the project members about the way of working. using this framework, 60 new demands on IT were identified that had not been found in the traditional models that were used by the case company for this project. The framework has also received promising feedback from validation workshops with a total of 178 participants.

6.5. Discussion on the VDHCP framework

The advantages of this framework is that it targets several of the aspects in literature and in the case studies. The development of the framework has contributed in closing the gap (which is still extensive) regarding the lack of empirical studies on how production system design is conducted and the fact that methodologies and process models dedicated to production equipment have less scientific coverage than their product-oriented counterparts. The framework can also contribute to coping with the increased system complexity. Additionally, the framework contributes to the increased need to focus the design of industrial systems to the whole sociotechnical system and addresses the current systems engineering practices which tend to view human considerations as an afterthought.

Through the validation workshops, it was identified that the approach supported the transfer of knowledge within and between development teams. The approach supported the building of models that are more clearly understood by designers, and the work also helped identify issues that were not addressed by any other team. The approach supported including humans in the systems right from the beginning. Aspects were identified that had not been addressed, so work groups were set up to design solutions. Participants stated that these methods help to manage risk. The method was also appreciated as being more rigorous in terms of documentation than previous projects, as one focus of the workshops was to document the concepts selected and develop a system concept for the input. It was stated that the workshops made the entire operation easier to understand as a system, and that it was possible to influence the development. Some statements highlighted the importance of gaining an overview that was lacking before, and the importance of cross-functionality and collaboration. It was also stated that with this approach, concepts can be developed more precisely and demands become more tangible. Some participants said that it takes some effort to understand the methods, but that using a more intuitive approach can be too simplistic. These are important aspects to consider going forward.

However, it has not yet been possible to evaluate the gaps in the effectiveness of the methods as the project will still be running for a few more years. To accept the usefulness of the method beyond the example problems, authors (Pedersen et al., 2000) suggest building confidence in the method's generalisability. They state that if the method is proved to be useful for some limited instances, then it can be stated that the method is empirically performance-valid. Thereafter, if the method is deemed useful beyond the example problems, it can be considered to be theoretically performance-valid. This still remains to be validated for the developed framework as the examples have all been in the battery production system design. For this reason, the proposed method cannot be considered theoretically performance-valid, although the results are still encouraging. Moreover, authors such as Ellis and Dix (2006) state that a large proportion of the design research methods and tools proposed in the literature are conducted in artificial settings and with small sample sizes, thus rendering them non-theoretically performance-valid. However, their results are still useful for industry and academia.

6.6. Reflections

The findings from the studies show promising results when it comes to addressing the engineering goals of managing risk and managing complexity within the scope of concept development of the production management part of a battery assembly industrial plant project. The Comprehensive Prescriptive Study approach was considered appropriate for this type of research. However, as the project is still at an abstract concept level, the goals are not as precise and measurable as the theory of the research methods proposes. From this perspective, the generalisability can be more difficult to prove. On the other hand, Design Research is also important in very early stages of development where the concepts have not yet been developed.

Some of these technical methods and concepts, such as simulation models and 3D generated films, have been used, although in other perspectives and with a smaller and more limited group of people, the engineers. What is new in this project is that all the actors in the production system are invited from production. Normally it is the engineering department that invites what is referred to as "stakeholders", where traditionally the human aspects are not specifically highlighted as in this project, which works with personas. Previously, personas have only been used from the central HR team. Working with and emphasising the importance of visual models for gaining understanding from all actors is also something new for the organisation. Still, one gap that was identified in the literature review was the insufficient commitment from functional departments. Their presence was increased in this project, although still not up to expected levels.

The feedback and validations were surprisingly positive for the researchers. However, reading Grashiller et al (2017) who state that often “the innovation management in the manufacturing industry is confronted with (…) stage-gate processes” and that “cost-triggered and time-critical project targets make uninhibited and open-minded thinking (…) difficult”, it is likely that the engineering projects had not explored these kinds of methods before. Even so, for example Kujala (2002), clearly states that usability and more accurate user requirements are achieved through the involvement of potential users in product development which supports the studied approach. Other reasons for the positive feedback could be that the teams found it fun to be part of a research project and to receive a lot of attention, and that the researcher is a manager at the plant, which could mean that participants felt pressure to show enthusiasm. Another unexpected finding was the fact that the participants felt that this was such a new way of working. These concepts have been available for a long time but, as the literature review also states, it appears they haven’t reached the engineering community in production system design. One reason for this could be that the company’s product design department gets a lot of resources – ten times the amount of resources in production system design – even though investments in the production systems are also large in scale. A reason why product development is prioritised could be bias from management: that the products themselves are far more important than the production system that will need to deliver these products at world-class levels for perhaps 20 years.

7. Verification and validation

As elaborated in Chapter 3, the work presented in this thesis follows two goals: to improve product development practice and to enhance knowledge about the process. To show that the research is valid, three points need to be proved: that it investigates a *valid problem (Le Dain et al., 2013)*, that the presented method *in itself works (Barlas & Carpenter, 1990)* and that it is *useful (Pedersen, Emblemsvåg, et al., 2000)* (Pedersen et al., 2000).

7.1. Validation of research gap

Following Le Dain et al. (2013), to validate research, it is necessary to answer the question: “Are you doing the right research? This question has been answered as follows, with regard both to the contribution to academic knowledge and to the engineering design practice:

7.1.1. Validation of the academic gap

Three research gaps have been identified from literature review:

a) The process of designing the production system has received little academic attention. This statement is validated by the authors below:
   - The process of designing the production system has received little academic attention and its potential for offering a competitive edge has largely been ignored (Bellgran & Säfsten, 2009).
   - Islam et al. (2020) state that “there is still a lack of empirical studies on how to conduct a production system design that targets the operational performance objectives already during the design phase, considering this a research gap”.
   - Vielhaber and Stoffels (2014) identified that in the academic world there is a greater focus on product development than on production development and that, in particular, methodologies and process models dedicated to production equipment have less scientific coverage than their product-oriented counterparts. Product development methods have been explored and adapted over many years.

b) Lack of systematic and effective systems engineering design methods in production system design. This statement is validated by the authors below:
   - Systems engineering and design methods have not yet been fully adopted by the manufacturing engineering community (Arista et al., 2023).
   - Stark et al. (2017) state: “Today’s manufacturing system design processes and architecture are still based on traditional engineering methods and can hardly cope with increased system complexity”. Stark et al. continue: “In reality, the manufacturing system design barely even follows a systematic design approach; it is still common practice to let each design engineer work within his or her own discipline by using specific design and engineering models (…) without any true systems engineering design opportunity”.

c) Lack of inclusion of human aspects in the production system design. This statement is validated by the authors below:
   - Several researchers have addressed the need to extend the focus of the design of industrial systems to the whole sociotechnical system (e.g. (Amokrane-Ferka & Hein, 2022; Cagliano et al., 2019; El-Haouzi & Valette, 2021; Gräßler et al., 2021; Madni & Orellana, 2018; Neumann et al., 2021; Stern & Becker, 2019).

- They claim that human actors are often greatly simplified in model-based design, thus disregarding individual personality and skill profiles.
- In complex systems, humans are often part of the complex system as opposed to being just users of the system, and current systems engineering practises tend to address human considerations as an afterthought (Madni & Orellana, 2018).

From these many-voiced statements, it can be concluded that the production system design engineering research community sees a definite academic gap regarding academic attention, systematic and effective methods and lack of inclusion on human aspects in the production system design.

7.1.2. Validation of the industrial problem

The industrial problem is formulated as follows: Considering the vast amounts invested in production systems, the running costs that they entail, and the fact that these systems are often kept in operation for decades, the attention from industry for systematic and effective systems engineering design methods in production system design is relatively low. This fact, together with the five identified transformational drivers for the powertrain production system engineering community, creates risks for the heavy truck industrial projects in terms of cost, performance and schedule. Examples could include cost overrun during development, risks of delivering a system that does not satisfy the needs when in use, resulting in late and expensive adjustments, unsatisfactory performance and poor work environment. As systems engineering methods aim to mitigate exactly these risks, it is critical for industry to apply such methods in order to design, build and operate production systems that accomplish the purpose safely in the most cost-effective way possible.

While the research gap could be validated through a review of literature, the need in the industry had to be validated through empirical studies. A total of seven studies in the case company (five case studies presented in this thesis plus two additional case studies), all referenced below, are used to validate the industrial problem.

- Paper A shows that reliability of equipment is of major concern and validated the importance of investigating systems engineering state of practice (Hagström et al., 2023).
- Paper B presents empiric data from four cases illustrating the need for improved knowledge and information management practices in the production system design and acquisition of production equipment. The cases demonstrate clear improvement potential when documenting and transferring knowledge and information about the current product towards the purchasing of new equipment. Known issues and problems are not satisfactorily transferred or requested by the purchasing team. The knowledge of the problems in the existing production machines should influence the buying of the new production machines to ensure the same problems does not occur again (Hagström et al., 2019).
- Paper D (under review), Paper E (under review) and Paper F (accepted at DESIGN 2024) identified that in earlier production system design projects, the engineering focus was more equipment-oriented than production system-oriented, which had led to problems in production. This new project with the overarching task of creating a production plant for a novel product saw the need to address this issue. (Papers under review)
- A previous case study, not included in this thesis, indicated that maintenance costs for new equipment continue to be an issue for the case company, and could possibly also be an increasing issue. To evaluate the effectiveness of the acquisition process, data

shows that recently purchased machines have a higher maintenance cost factor than old machines nearing their end of life, and that maintenance problems related to design issues account for 26% of the total number of breakdowns (Hagström et al., 2020)

- Another previous study investigating the documentation quality of production equipment acquisition, not included in this thesis, indicated that incomplete or missing input as well as the quality of the input could impact the acquired machines' performance and the project's performance (Hane Hagström et al., 2022).

7.2. Validation of the design method Visual Design for Human Centric Production (VDHCP)

The process of validating a design method involves demonstrating the usefulness of the design with respect to its intended purpose (Pedersen et al., 2000). Usefulness is evaluated through effectiveness; the method efficiently provides the correct Design Support. In this context, a correct DS has an acceptable performance and is developed with less cost and time (Pedersen et al., 2000; Seepersad et al., 2006). To demonstrate the usefulness of the design method proposed in this thesis, the validation square was applied, as illustrated in Chapter 3 and Figure 49.

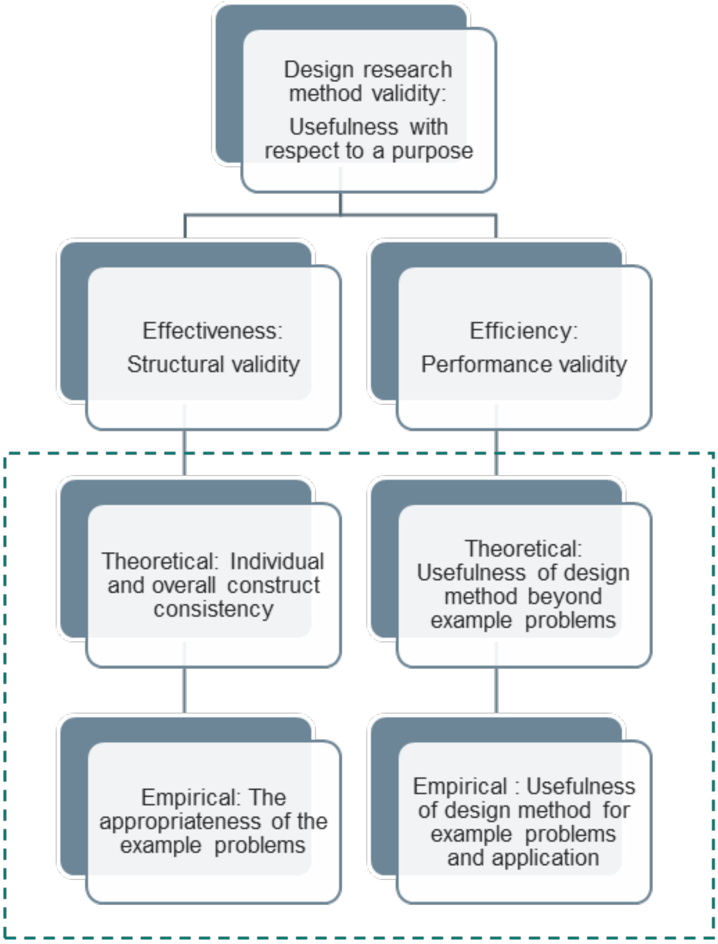


Figure 49: The validation square redrawn from Seepersad et al. (2006) and (Pedersen, Emblemsvag, et al., 2000)

7.2.1. Theoretical and structural validity

Accepting the construct validity is related to demonstrating the validity of all the different pieces used to conform the proposed model or method.

Accepting construct validity:

The developed Design Support framework, called Visual Design for Human Centric Production (VDHCP), consists of well-established methods from other disciplines that were not yet well established in the production system design community when designing human-centric production systems for novel products.

- Technical process assessment: To establish where a project is in maturity. From the handbook of INCOSE (2020) the technical processes and how needs are transformed to requirements are described
- Concept of Operations: ConOps/OpsCon can be considered as a transitional design artefact that plays a role in the requirements specification during the early stages of the design and involves various stakeholders (Kaasinen et al., 2022; Madni & Orellana, 2018)
- Design Thinking: According to Purdy and Popan (2023), "Design thinking is a thought process that depends on examining all sides of an issue from both a practical and a creative perspective in a (…) solution-focused thinking". They continue: "The major aspects of design thinking are understanding the practical and emotional needs of a client, using prototypes or physical models to explore possible ways of achieving goals"
- Model-based Systems Engineering: As defined by Estefan (2007) "MBSE methodology can be characterized as the collection of related processes, methods, and tools used to support the discipline of systems engineering in a 'model- based' or 'model-driven' context". Estafan continues by stating that MBSE is about "elevating models in the engineering process to a central and governing role in the specification".

Accepting method consistency:

Accepting method consistency is related to building confidence in the way the constructs work together. For this purpose, authors recommend the use of flow charts (Pedersen et al., 2000) for evaluation of the consistency of the method proposed in this thesis. The information flow presented in Figure 50 suggests that the information generated from each construct is adequate and necessary for interaction with the other constructs.

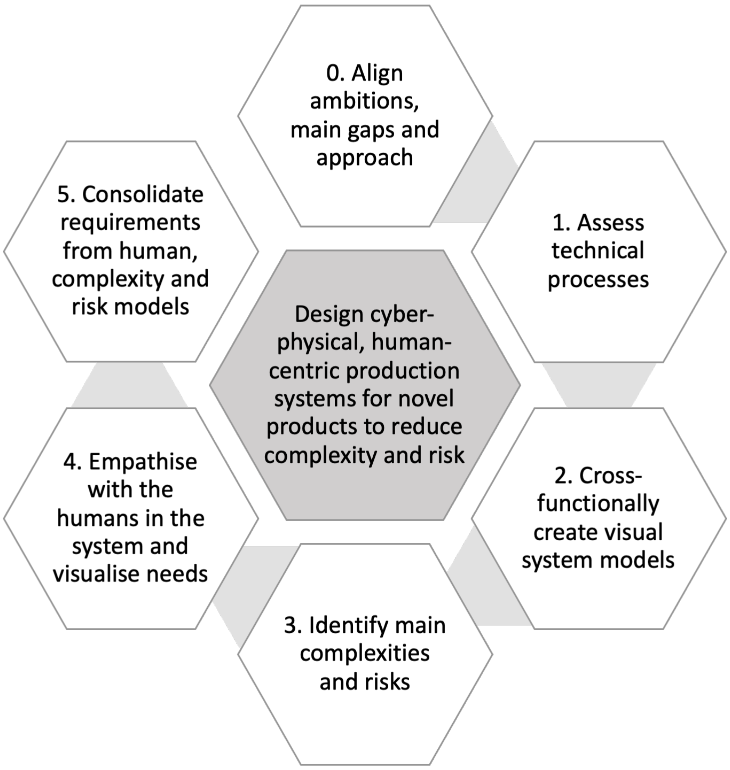


Figure 50: Visualisation of the framework Visual Design Human Centric Production (VDHCP) as a Design Support to Production System Engineering with the aim to design cyber-physical, human-centric production systems for novel products to reduce complexity and risk

Accepting both construct validity and method consistency can also be interpreted as "being logical." According to Olewnik and Lewis (2005), being logical is the first requirement for a design support tool (the proposed framework) to be valid. Moreover, the step of accepting method consistency through an information flow suggests that the method and framework use meaningful and reliable information, which is the second requirement for the validation of decision support tools (Olewnik and Lewis, 2005). Meaningful information indicates that insights into the interdependencies of constructs are provided and make sense. As the framework is meant to be used by industrial practitioners during conceptual phases of production system design, it can be established that the information that will enter the platform is reliable (i.e., it comes from appropriate sources).

7.2.2. *Empirical structural validity: Accepting the example problems*

In this instance, confidence must be built on the appropriateness of the example problems chosen to verify the proposed method. Authors (Pedersen et al., 2000) suggest (1) proving that the example problems are similar to the problems for which the method constructs are accepted and (2) proving that the example problems are representative of the problems the method is supposed to address. The evaluation of the method's usefulness was performed in Paper F, which was based on evaluations of usefulness in Paper D and Paper E, reflecting the production system design for a battery assembly plant.

7.2.3. *Empirical performance validity: Accepting the usefulness of the method for some example problems*

To accept the usefulness of the method, authors (Pedersen et al., 2000) suggest applying the method to solve representative example problems. Then, usefulness must be proved to be linked to the method application. Metrics for usefulness are related to the degree to which a purpose has been achieved. Paper F validated the usefulness for a similar example, reflecting the production system design for a battery cell plant, albeit only with a small group of twelve senior executives.

7.2.4. Theoretical performance validity: Accepting the usefulness of the method beyond example problems

To accept the usefulness of the method beyond the example problems, authors (Pedersen et al., 2000) suggest building confidence in the method's generalisability. They state that if the method is proved to be useful for some limited instances, it can be stated that the method is empirically performance-valid. Thereafter, if the method is deemed useful beyond the example problems, it can be considered to be theoretically performance-valid. This has yet to be validated for the developed framework as the examples have all been in the battery production system design. For this reason, the proposed method cannot be considered theoretically performance-valid, although the results are still encouraging. Moreover, authors such as Ellis and Dix (2006) state that a large proportion of the design research methods and tools proposed in the literature are conducted in artificial settings and with small sample sizes, thus rendering them non-theoretically performance-valid. However, their results are still useful for industry and academia.

8. Conclusions

This chapter outlines the outcome of the work presented in this thesis in the form of conclusions and recommendations for further research

The findings presented in this thesis should be seen in the context of the preceding literature reviews and case studies presented. The industrial problem is summarised as risks for novel powertrain production system design projects in terms of cost, performance and schedule due to late identification of system requirements. The research gaps are summarised as a lack of systematic and effective systems engineering design methods in production system design and a lack of inclusion of human aspects in the production system design. The synthesis of the industrial problem and the research gaps indicates that a framework is needed for production system design for novel products in order to mitigate risks in terms of cost, performance and schedule due to late identification of system requirements.

8.1. Contributions and claims for academy and industry

The work presented in this thesis tests and validates the research claim by answering four research questions. The central research claims are formulated as follows:

- **Claim 1**: The synthesis of the current industrial problem and the research gaps indicates that a framework is needed for human-centric production system design for novel products in order to mitigate risks in terms of cost, performance and schedule due to late identification of system requirements.
- **Claim 2**: The VDHCP framework, combining the system engineering methods of Concept of Operations and Model-based Systems Engineering with creative cross-functional workshops and visual models, could be developed to support powertrain production system design engineers to identify system requirements early when designing human-centric production systems for novel products.
- **Claim 3**: The VDHCP framework supports powertrain production system design engineers to identify system requirements early when designing human-centric production systems for novel products, as 60 previously neglected new IT demands were identified and hence mitigated the risks in terms of cost, performance and schedule due to late identification of requirements.

The research results, development and validation have been presented in six core publications (Paper A through Paper F) which form the content of this thesis. The VDHCP framework's contribution to academy and applied production system design has been shown in three studies in collaboration with industrial practitioners. The framework has been validated in a laboratory environment, which would correspond to TRL 4, and realised in a proof-of-concept tool. From this, it can be concluded that the framework does support production system design for novel products in order to mitigate risks in terms of cost, performance and schedule due to late identification of system requirements.

As stated in Chapter 7, the usefulness of the method beyond example problems cannot be proven in this study, although the results are encouraging. There are no apparent prerequisites hindering why this approach should not be able to support powertrain production system design engineers in all levels of innovation (Evans et al., 1972): Radical breakthrough innovation, major innovation, incremental innovation and improvements but needs to be explored further.

8.2. Future work

Recommendations for future work include exploring further what the production system design engineering community could harvest from the product development and community, and if these methods would have any actual impact on project cost and lead time overruns, workload of engineers and better production systems in terms of resilience, sustainability and human factors. Further research is proposed to focus on the implementation of frameworks in system engineering design methods in production system design, in particular for novel products, where a large amount of new knowledge needs to be developed. In addition, further research on the integration of human factors into production system engineering design is required to prepare for future generations of workers. Finally, there is a need to explore further how the production system design engineering community can learn from the product development community and to identify whether these methods would have any actual impact on project cost and lead time overruns, the workload of engineers and better production systems in terms of resilience, sustainability and human factors.

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