Development of a Comprehensive Product Lifecycle based on Data of Smart Factories and Smart Products

by

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Declaration

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Abstract

Trends of customisability and innovation in products influence the way companies develop products. Customers want products that meet their individual requirements through a high degree of customisation. Mass customisation was created to meet this demand. With mass customisation product diversity increases and product generations are changed more frequently. This often results in higher costs since the product engineering process is not familiar with the new product types. From the companies' point of view, this situation is complicated by the trend that product development processes are being shortened, and companies need to get their products to market faster. This forces companies to develop more complex products in more complex environments and to bring them to market quicker. Also, current product lifecycles consider only one product generation and no product diversity. Moreover, product engineering and the subsequent phases are often separated from each other. Due to this silo working, knowledge cannot be transferred further, mistakes are made repeatedly, and product engineering teams cannot use the feedback from smart factories and smart products. For this reason, potentials offered by the use of smart factory and smart product data for smart, customisable product families are not being exploited in current product lifecycles. To exploit the potentials, a novel product lifecycle i²PLM is created in this thesis. A mixed literature review is used to evaluate current product lifecycles and to create a reference process. Also, challenges and cause-and-effect relationships are identified in the overall context of the product lifecycle. The findings result in defining data streams and relevant data in a product lifecycle. The data streams and relevant data are incorporated into the reference process, creating a novel product lifecycle called i²PLM. The i²PLM consists of six components. The different components provide, among other things, an overview of the main phases of a product lifecycle and the current status of the product portfolio. One of the components represents the organisational processes and another the business processes. The core component of i²PLM is the product lifecycle database, which enables the implementation of data generation and analysis with its processes. The i²PLM is validated within the scope of an experiment. The validation takes place in an industrial research environment at the University of Reutlingen. The content of the experiment is the development of a smart product variant based on production and use data. Further research is recommended for the applicability and implementation methods of i²PLM in business practice, as well as for the automatic generation of cause-and-effect relationships.

Keywords: product lifecycle management: product engineering process; i²PLM; smart customisable product families; mass customisation, lifecycle engineering; CPS

Opsomming

Tendense van aanpasbaarheid en innovasie in produkte beïnvloed die manier waarop maatskappye produkte ontwikkel. Kliënte wil produkte hê wat aan hul individuele vereistes voldoen deur 'n hoë mate van aanpassing. Massa-aanpassing is geskep om aan hierdie vraag te voldoen. Met massa-aanpassing neem produkdiversiteit toe en produkgenerasies word meer gereeld verander. Dit lei dikwels tot hoër koste aangesien die produk-ingenieursproses nie vertroud is met die nuwe produktipes nie. Uit die maatskappy se oogpunt word hierdie situasie bemoeilik deur die neiging dat produkontwikkelingsprosesse verkort word, en maatskappye moet hul produkte vinniger op die mark kry. Ook, huidige produklewensiklusse neem slegs een produkgenerasie en geen produkdiversiteit in ag nie. Boonop word produkingenieurswese en die daaropvolgende fases dikwels van mekaar geskei. As gevolg van hierdie silowerk kan kennis nie verder oorgedra word nie, foute word herhaaldelik gemaak en produkingenieurspanne kan nie die terugvoer van slim fabrieke en slim produkte gebruik nie. Om hierdie rede word potensiaal wat deur die gebruik van slim fabrieks- en slimprodukdata vir slim, aanpasbare produkfamilies gebied word, nie in die huidige produklewensiklusse ontgin nie. Om die potensiaal te ontgin, word 'n nuwe produklewensiklus i²PLM in hierdie tesis geskep. ’n Gemengde literatuuroorsig word gebruik om huidige produklewensiklusse te evalueer en om ’n verwysingsproses te skep. Ook, uitdagings en oorsaak-en-gevolg verhoudings word geïdentifiseer in die algehele konteks van die produk lewensiklus. Die bevindinge lei tot die definisie van datastrome en relevante data in 'n produklewensiklus. Die datastrome en relevante data word in die verwysingsproses geïnkorporeer, wat 'n nuwe produklewensiklus genaamd i²PLM skep. Die i²PLM bestaan uit ses komponente. Die verskillende komponente verskaf onder meer 'n oorsig van die hooffases van 'n produklewensiklus en die huidige status van die produkportefeulje. Een van die komponente verteenwoordig die organisatoriese prosesse en 'n ander die besigheidsprosesse. Die kernkomponent van i²PLM is die produklewensiklusdatabasis, wat die implementering van datagenerering en -analise met sy prosesse moontlik maak. Die i²PLM word bekragtig binne die bestek van 'n eksperiment. Die validering vind plaas in 'n industriële navorsingsomgewing by die Universiteit van Reutlingen. Die inhoud van die eksperiment is die ontwikkeling van 'n slim produkvariant gebaseer op produksie- en gebruiksdata. Verdere navorsing word aanbeveel vir die toepaslikheid en implementeringsmetodes van i²PLM in sakepraktyk, sowel as vir die outomatiese generering van oorsaak-en-gevolg verhoudings.

Sleutelwoorde: produklewensiklusbestuur: produk-ingenieursproses; i2PLM; slim aanpasbare produkfamilies; massa-aanpassing, lewensiklusingenieurswese; CPS

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List of acronyms

ACED	Abstract Cause-and-Effect Diagram
AI	Artificial Intelligence
AR	Augmented Reality
BOM	Bill of Material
CAD	Computer Aided Design
CC	Cause class
CER	Cause-and-Effect Relationships
CED	Cause-and-Effect Diagram
CPS	Cyber-physical systems
DCED	Detailed Cause-and-Effect Diagram
ERP	Enterprise Resource Planning
HitL	Human-in-the-Loop
HitM	Human-in-the-Mesh
KPI	Key Performance Indicator
M2M	Machine-to-Machine
MIMB	Modular Intelligent Mobility Box
NFC	Near-field communication
I4.0	Industry 4.0
IoT	Internet of Things
PC	Problem class
PLC	Product Lifecycle
PLM	Product Lifecycle Management
RAMI4.0	Reference Architecture Model industry 4.0
RFID	Radio Frequency Identification
SOC	Security Office Centre

VDI	Association of German Engineers (German for “Verein Deutscher Ingenieure”)
VM	Virtual Manufacturing
VR	Virtual Reality

Chapter 1 Introduction

The thesis begins with an overview of the background of the study. Chapter 1 contains the basic information for processing the research project with the title “Development of a comprehensive product lifecycle based on data of smart factories and smart products”. This chapter presents the initial situation in the first subchapter. With this base, the research problem statement and the research questions are defined in the following subchapter. Based on the research questions, the objectives follow in the next chapter.

1.1 Initial situation and background of the research

Currently and as a trend, the market requires a high degree of customisation and innovations. People like to have individualised products that fit their individual needs (Sikhwal & Childs, 2017, p. 674). But these products must first be developed. A crucial factor in gaining and maintaining a competitive advantage is a company's ability to develop successful new products and bring them to market (Müller-Stewens & Möller, 2017, p. 158).

The phases of a product from development to the start of production are called the product engineering process. If the product engineering process is extended to include the use and end-of-life phases, this is referred to as a product lifecycle. If you look at current product engineering processes, the development of the product and the development of the production system are mainly separated from each other. They are also most of the times not coordinated with each other (Mandel et al., 2020, p. 3).

As described, there is a trend in the individualisation of mass products (Wang et al., 2017, p. 311). The answer for this trend from the production side is called mass customisation.

To build the individualised products, components must have a variable product architecture that is adaptable to changes and new technologies (Richter et al., 2010, pp. 128-134). Variable product architecture describes a system of components with interfaces from which a variety of products can be assembled.

Complicating the situation, there is a trend to shorten development cycles due to increasing competition, which means that new product generations are created more frequently. As an example, between 1997 and 2015 product variety has increased by about 150 % and product engineering processes have been reduced by 30 % (Douma et al., 2019, p. 5).

Given in current product engineering processes that both, the development of the product, and the development of the production system are mainly separated from each other, working in (data) silos leads to the loss of potential for cross-value chain data integration. In centralised data platforms, more information and knowledge about the company can be stored and cross-divisional analyses of the data can take place. Potential savings of 20 % are expected in marketing, sales, research, development and quality management and over 10 % in production. (Günther et al., 2022, p. 188)

The initial situation can be summarised from both the customer's and company's side. On the one hand, customers are demanding greater customisability of products. This also increases product diversity. On the other hand, however, product engineering processes are being shortened and product generations are being changed with ever-increasing frequency. This forces companies to develop ever more complex products in more complex environments more efficiently and to bring them to market more quickly.

1.2 Research problem statement and questions

In general, most product engineering processes consider only one product generation. This does not correspond to the actual situation where successful products have more than one generation (Nourbakhsh et al., 2016, p. 2 & 8).

Also, the product development is separated by the development of the production system with the result that the product development does not take into account the characteristics and limitations of the available production environment. This is why it is difficult to estimate effects and risks of changes to the product and to develop different variants (Mandel et al., 2020, p. 3).

Furthermore, the development teams do not use feedback from data after market entry and designers have the problem of design fixation. This means that they adhere to previous designs, which leads to a duplication of work, and to difficulties in the adaption to individualised products and to rare innovations (Stempfle, 2011, pp. 116-129).

The production of those customised products is called mass customisation. Most of the problems in implementing mass customisation are related to the design and development phase (Duchi et al., 2014, pp. 320-327). With mass customisation one mostly have conflicting goals between standardization and differentiation (Krause et al., 2021, p. 351).

When developing the products for mass customisation there is the problem that the product costs increase by 20 % on average when doubling the product variety (Gauss et al., 2021, p. 265). To counter this problem a new product engineering process is necessary which also uses the features of cyber-physical systems and their data processing capabilities (Lee & Lee, 2015, pp. 431-440).

Furthermore, there is a research gap on product adjustability and the product engineering process in the context of Industry 4.0 (Mandel et al., 2020, p. 3; Pessoa & Jauregui-Becker, 2020, p. 175). This research gap includes the fact that there are no mechanisms developed yet that use the data obtained by smart product and smart factory for smart product design (Tomiyama et al., 2019, p. 12).

Summarising the problem, in existing product lifecycles, the potentials offered by the use of smart factory and smart product data for intelligent, customisable product families are not being exploited. The research problem statement is shown in the following Table 1.

Table 1: Research problem statement.

Research problem statement	In existing product lifecycles, potentials offered by the use of smart factory and smart product data for intelligent, customisable product families are not being exploited.

Thus, the data from the smart factory and smart products is not used for the product and process engineering of customisable, intelligent products due to the separation of product and process engineering and subsequent phases. This means that the potentials for customisability, for improvement within product families and between product generations are not fully exploited. This can lead to major adjustments in the smart factory and to an increase in production and development costs, as the effects and risks of changes are difficult to assess. The costs could also increase due to an unrealistic testing environment.

These problems are also relevant for South Africa due to the fact that South Africa is leading the industry to build smart factories using Industry 4.0 technologies and mass customisation, as the technology of Industry 4.0, is globally relevant. Mass customisation is a globally relevant trend caused by the increasing individuality of customers.

Furthermore, from the economic point of view, South Africa wants to enhance their position in the global market, and this is why it is one of the five emerging economies of the BRICS-Association. South Africa’s most exported products are machines, vehicles and technical products which are all products with a wide variety and different variants. In most of the cases, South African products are produced for buyers from foreign countries. In the product engineering processes often local modifications are required to meet contextual factors for the production of global products (Mund et al., 2015, p. 705).

To increase worldwide competitiveness South Africa built up a program to exploit the potential of the technical innovations of Industry 4.0 and thus boost the economy. Manufacturers are motivated to focus on smart manufacturing (Bag et al., 2021, p. 1). To consider the production environment in product engineering of individualised products, Industry 4.0 technologies must be used, and relevant data must be collected.

Based on the research problem statement the following research questions for the master thesis can be derived, which are presented in the following Table 2.

Table 2: Research questions.

Research question 1	What are the challenges in product and process engineering for customisable smart products, and which data and information from the smart factory and smart products can reduce these challenges?
Research question 2	What does an approach look like in which smart factory and smart product data are collected and used in product and process engineering?
Research question 3	How can the approach for generating, storing and using smart factory and smart product data be integrated into the product lifecycle for the development of customisable smart products?

The research questions are subdivided into three questions. The first question is to identify fundamentally where challenges currently exist in the development of customisable products and which data can solve these challenges. The second research question asks for an approach on how this data can be collected and used in product engineering. Research question three asks about the possibility of integrating this approach into a product lifecycle with which customisable smart products can be developed.

1.3 Research objectives

In order to solve the problems and answer the questions, research objectives were defined for this master's thesis. In the following the primary objective and the derived secondary objectives are described and presented in the following Table 3.

The primary objective of this master's thesis is to create an integrated and intelligent product lifecycle that uses smart factory and smart product data for the development of customisable smart product families. This includes the creation of a process map in which all processes of the product lifecycle are visible and which also contains mechanisms for the use of smart factory and smart product data.

Table 3: Research objectives.

Primary objective	Creation of an integrated and intelligent product lifecycle that uses smart factory and smart product data for the development of customisable smart product families.
Secondary objective 1	Identification of relevant data and information of smart factories and smart products for the product and process engineering of smart customisable product families.
Secondary objective 2	The development of an approach to use the smart factory and smart product data in a product lifecycle.
Secondary objective 3	Integration of the approach into a product lifecycle which has processes that generate, store and use data and information of smart factories and smart products for the development of customisable smart product families.

This primary objective is divided into three secondary objectives. The first of these secondary objectives is to identify relevant data and information of smart factories and smart products for the product development of smart customisable product families. This first secondary objective is related to the first research question. The development of an approach to use the smart factory and smart product data in a product lifecycle is the second secondary objective and it refers to the second research question. The third secondary objective is the integration of the approach into a product lifecycle which has processes that generate, store and use data and information of smart factories and smart products for the development of customisable smart product families.

Chapter 2 Research design and methodology

In this chapter, the scientific-theoretical positioning, the research design and the research methodology are shown. The limitations of the research thesis are described in the following subchapter. The outline and structure of this master's thesis are shown in Chapter 2.4. The introductory chapters end with a conclusion of the key aspects.

2.1 Research design

The research design forms an overall structure that is used to achieve the research objectives. Since the research work is intended to develop a result (so-called artefact) which is to be created through a practice-oriented research approach, this work will focus on the guiding principles of Design Science Research. The focus relating to this is more on the contribution to results and less on the contribution to knowledge. On the one hand, the proximity to practice can lead to higher applicability due to more frequent validation and feedback. Still, on the other hand, this also influences the independence of the researchers from the object of investigation (Benner-Wickner et al., 2020, p. 4).

According to (Hevner et al., 2004, pp. 82-90), design science research is based on seven guiding principles. These include:

1. Artefact design: the creation of a result/artefact.
2. Problem relevance: the artefact must solve a practice problem.
3. Design evaluation: a methodological evaluation of whether the artefact solves the problem.
4. Research contribution: a general research contribution must be made.
5. Research rigour: Design and evaluation must be methodologically correct.
6. Design as an optimisation problem: The result is incrementally developed to completion.
7. Publishability: The research contribution must be accessible to the scientific community.

Various models have been proposed in the literature to transform the guiding principles of design science research into an applicable model. One of them is the model according to Österle. This model includes a four-stage cognition process with the iterative phases analysis, draft, evaluation and diffusion (Benner-Wickner et al., 2020, pp. 5-8).

Due to its applicability, Österle's model is used for this thesis. A derivation and adaptation of the phases to the research project is shown in the following Figure 1.

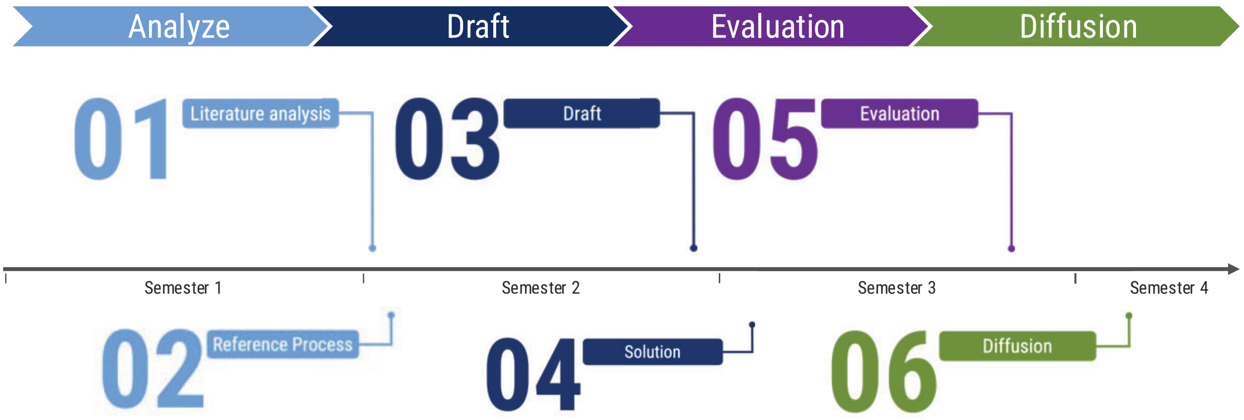


Figure 1: Design Science Research based on (Oesterle et al., 2010, pp. 667-668).

The model starts with the analyse phase, where a basis for the research is built. In this section of the study, the general conditions of the artefact are elaborated. This results in concrete requirements for the artefact. At this stage, the literature is analysed, and a reference process is selected.

The next step is the draft phase, where the reference process is adapted to the research objectives, and the artefact is systematically generated. At this stage, a draft and a solution approach for a new product lifecycle are developed.

The applicability of the artefact of the new product lifecycle to the defined case is evaluated in the evaluation phase. The results of the evaluation phase are used to improve the product lifecycle.

The last step is to write the results in a joint master thesis and a joint scientific paper (Oesterle et al., 2010, pp. 667-668).

Summarising the chapter, the research design is oriented on the Design Science Research Model of (Oesterle et al., 2010, pp. 667-668), starting with the steps “analyse”, “draft”, “evaluation”, and “diffusion”.

2.2 Research methodology

In the following, the scientific-theoretical positioning and the methodology of the research work are presented. The positioning of the standpoint on reality and knowledge acquisition is described.

Since human knowledge is fallible, the own analyses, realisations, hypotheses, and theories are regarded as fallible according to fallibilism.

In the context of ontology, the standpoint of realism is taken within the work. It is assumed from a reality existing independently of the recognising subject.

The acquisition of knowledge in the context of epistemology takes place within the work on the basis of rationalism. It is thus assumed that reality gains knowledge through human reason. The knowledge about the improvement potentials by the application of the methods compiled in the research work is recognisable by thinking and acting.

The work is written from a normative point of view in compliance with ethical rules, and the knowledge of other authors is used and identified accordingly.

The scientific knowledge process is based on a hypothetical-deductive research methodology. Hypotheses or statement systems are established for the cause-and-effect relationships of the data from the Smart Factory and Smart Products. From this, test sets for observing phenomena are developed (Popper, 1989, p. 7 f.). At the beginning, the problem from the research area is considered, and then several hypotheses are made to solve the problem. In the next step, the hypotheses' validity is tested by application examples to increase their truth content by modified hypotheses. There is a possibility that the hypotheses are falsified. The methodology approach aims to link experience as a method and testing authority with the deduction procedure (Töpfer, 2012, p. 114).

2.2.1 Analyse phase

In the analyse phase, the subject area is examined from the ground up, and fundamental knowledge is built. This phase is crucial to analyse the state of the art correctly and to be able to evaluate the topic properly.

A mixed literature analysis with a focus on snowballing is conducted. The mixed literature analysis has the advantage of identifying foundational literature as well as recent research articles. With the analysis, relevant data and information of the Smart Factory and Smart Products for the development of smart customisable products will be identified.

The process for the literature analysis in the analyse phase is shown in the following Figure 2:

Figure 2: Literature analysis process.

After starting the literature review, a base of relevant literature is identified using search terms. The search terms, as well as their synonyms, super- and subordinates and similar terms are presented in the following Table 4.

German and English literature published between 2010 and 2022 is considered. The search was mainly conducted in the literature databases Google Scholar, Web of Knowledge, and in the libraries of Reutlingen University and Stellenbosch University.

Table 4: Search terms for this research.

Term	**Synonym**	**Superordinate**	**Subordinate**	**Similar**
Smart factor*	Intelligent factor*, ubiquitous factor*	Industry 4.0, made in China 2025, production 2030	Cyber-physical systems, big data, automation	Smart manufacturing, intelligent manufacturing
Product lifecycle	Product life cycle, product life-cycle	Business Process Management	Product engineering process, product development process, product engineering model, product development, product engineering, process engineering, production, use phase, end-of-life	New product development, product lifecycle management, PLM
Mass customization	Mass customisation	Smart factor*, industry 4.0	Self customization, modularization	Mass personalization

After a selection of literature has been made, the literature basis is evaluated, and literature is further selected if necessary. Subsequently, snowballing starts with this basis, which is shown schematically in the following Figure 3.

The snowballing procedure consists of a forward and backward search. In both forward and backward searches, literature can be included in or excluded from the literature base. However, before the literature is included, it should be fully reviewed. This process is repeated until no new literature is found (Wohlin, 2014, p. 4).

The literature analysis focuses on where challenges in product and process engineering of customisable smart product families occur. Cause-and-effect relationships are identified on this basis. Proposed solutions based on data streams are determined for the cause-and-effect relationships. Relevant data types are identified from this

Also, research at state-of-the-art product lifecycles will be conducted, where factors of success and challenges can be identified. To get an overview of which data can be used at which point in a product lifecycle, it is essential to first identify and classify these data types.

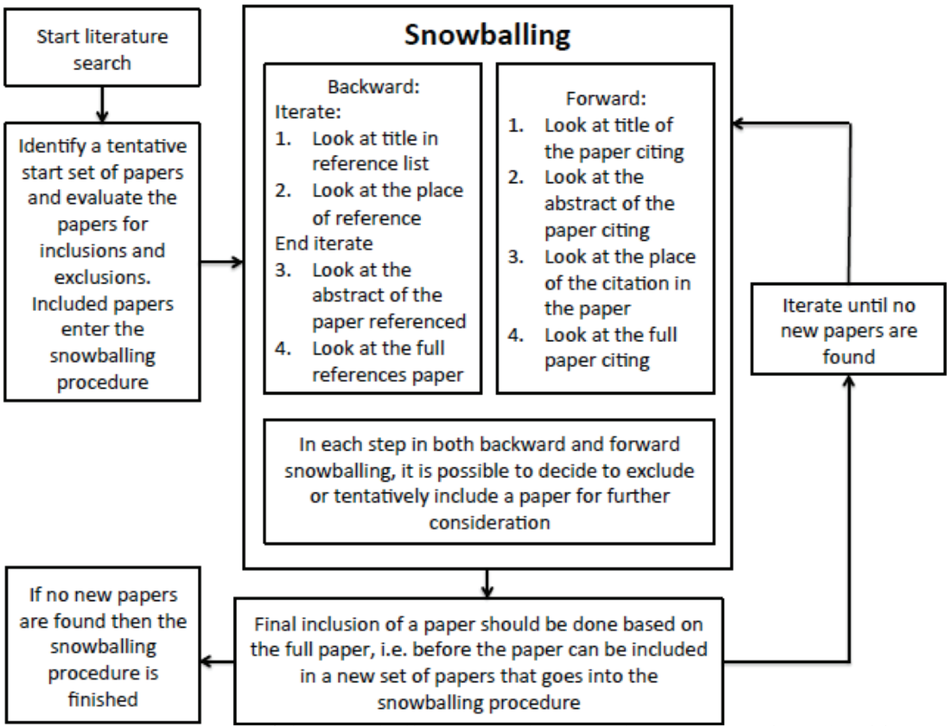


Figure 3: Schematic illustration of the snowballing procedure in a literature analysis (Wohlin, 2014, p. 4).

To get an overview of the literature and its connections, a network representation is created, which can be seen in the following figure. The literature overview is structured by the topics “Process”, “Cause-and-effect relationships”, “Generative Design”, “Mass Customisation”, and “Smart Factory”. If a source also includes more than one topic, it is shown by an arrow. Additionally, the type of the source is shown in Figure 4.

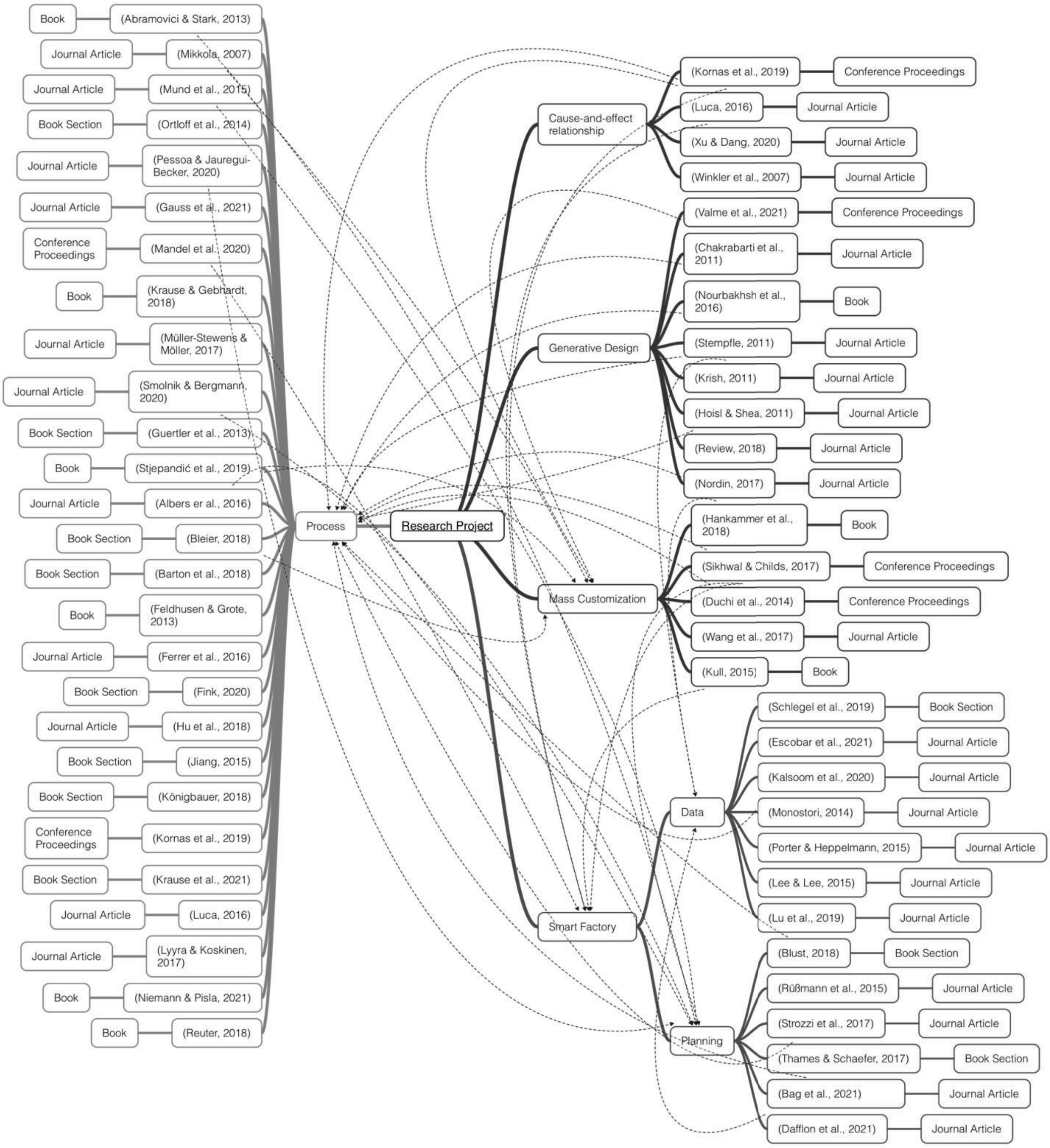


Figure 4: Literature analysis network.

2.2.2 Draft phase

The draft and solution approach of the new product lifecycle are developed in the draft phase. The schematic procedure is shown in the following figure. The aim of the new product lifecycle is to make the development of smart, customisable product families more efficient based on data from smart factories and smart products.

The creation of the solution approach takes place on the one hand, through the use of reference processes as a basis and, on the other hand through the cause-and-effect relationships methodology. In the analysis phase, reference processes are analysed. These are sorted out in the draft phase and merged into a single reference process. After simplifying and optimising the reference process, the adaptation of the reference process takes place on the basis of the cause-and-effect relationships.

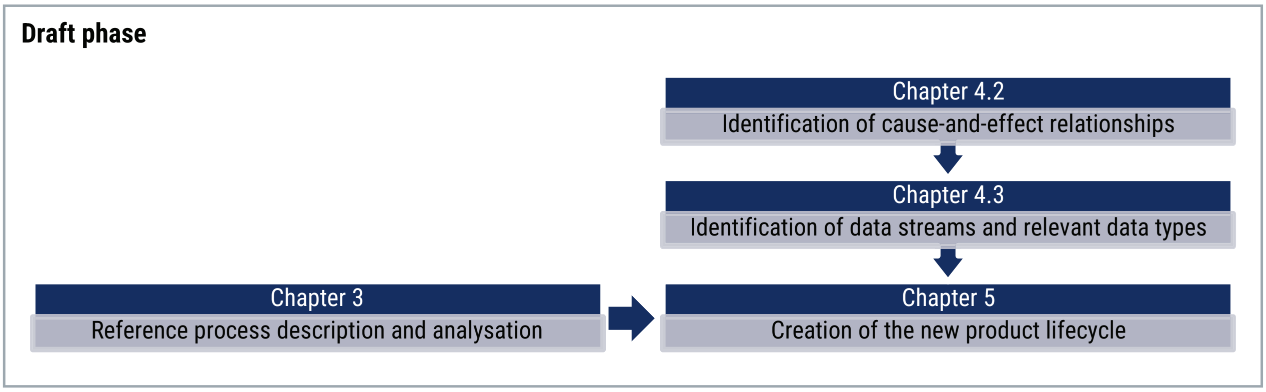


Figure 5: Draft phase procedure.

The first step to adapt the reference process to the product lifecycle is to analyse product lifecycles based on their cause-and-effect relationships. This serves to identify problems in the development, production, use and end-of-life of smart products. Causes that are related to the problems are identified and solutions for solving the problems proposed. In the process of finding solutions, relevant data types are identified by which the problems can be solved. This is the first research goal. When identifying the data types, the phases in which the data is generated are also recognised. This mapping is used to develop relevant data streams in the product lifecycle.

These data types and data streams are used for creating an approach for capturing and using data from smart factories and smart products. The approach is used as a basis for various data sources along the product lifecycle. The development of an approach to use the smart factory and smart product data in a product lifecycle is the second research goal.

The integration of the approach for generating, using and analysing data into the product lifecycle is the third research goal.

In order to use the data as efficiently as possible, technologies such as generative design are also being considered, and solution approaches are being developed in this context. For example, generative design approaches can be created taking into account the characteristics and limitations of the available production environment or user data. These characteristics and limitations can be, for instance, the installation space, mounting in machines, production techniques, free space for tooling or feedback from quality data.

The event-driven process chain method is used to model the product lifecycle. This is a graphical modelling language standard for describing processes.

2.2.3 Evaluation phase

The solution is evaluated in the evaluation phase. In this stage, the applicability of the product lifecycle is validated by means of an experiment.

The experiment will take place with an example smart product in a smart factory that is part of an industrial research environment. Within this phase, the subsequent generation of a smart lunchbox is developed based on production and sensor data.

Within the scope of the experiment, product and production characteristics are compared, and an evaluation of advantages, disadvantages in the applicability take place. With these findings further potentials will be derived. The results of the validation give indications for further optimisations of the product lifecycle.

2.2.4 Diffusion phase

In the diffusion phase, the results of the research are incorporated into the joint master thesis and joint scientific paper. The joint master thesis is submitted at Stellenbosch University and Reutlingen University.

Knowledge and theories are built up throughout the work, which enables the preparation of the two scientific works takes place during the whole time.

2.3 Limitations

In the following section, the limitations of the research are described. Because companies and their processes are usually very specific and depend on the company, business, product or service individually, the developed product lifecycle is not generally applicable. This work is limited to specific products that use the following features, which are derivations of the research problem:

- The development of modular product structures envisaged
- Focus on products with multiple generations
- Products are part of a product family
- Development of smart products
- Integration and production of products in a smart factory

- Consideration of the complete lifecycle from idea to end-of-life

This study is unable to encompass the entire field of business processes. This is why the focus lies on technical processes like product and process engineering or production and not on economic processes like product cost calculation or marketing.

This study cannot validate the entire phases of a product lifecycle in general, but only the applicability of an example product in certain phases of the product lifecycle. The reason for this is that a product lifecycle is significantly longer than the time available for the master's thesis. In addition, all activities related to the product lifecycle are time-consuming in their entirety, which means that no quantitative validation can be carried out.

Since CAD software from Dassault Systèmes is used in the current research environment, this is also used for the experiment.

2.4 Research study outline

The master's thesis started with a brief introduction in the form of a description of the initial situation, the problem, the relevance, the aims of the work and the limitations of the research. Within this Chapter 2.4, also the methodology is shown.

In the following chapter, the current state of research is shown. This chapter provides a basis for creating common definitions for the fundamental subject areas and technical terms. It includes the results of the mixed literature analysis. It could be assigned to the analyse phase of Österle's design science research.

After defining a theoretical basis, the relevant data of smart factories and the use phase for product engineering are identified. This is done by identifying cause-and-effect relationships between all phases of the product lifecycle. This chapter can also be assigned to Österle's analyse phase.

By using the research basis and the cause-and-effect relationships, a comprehensive product lifecycle using data from smart factories and smart products is developed and explained. The final draft and the result of the research are presented within this chapter, whereby it can be allocated to the draft phase of Österle.

The solution approach is validated in an industrial research environment in the following chapter to assess the applicability of the design. The chapter corresponds with Österle's evaluation phase from Österle. Here, the validation product is described first, followed by the experiment. After applying the validation process, the results and further optimisations are shown.

The main findings of the research will be summarised in Chapter 7, “Summary and conclusion”. Conclusions are drawn, and recommendations for further research are defined. The contribution to science is shown as well as a summary of the research limitations and recommendations for further work.

2.5 Conclusion

The introductory chapter builds the first entry into the master thesis. The area of research is outlined in the first subchapter 1.1, “initial situation”.

Thereafter, in the subchapter 1.2 the research problem statement, the research problem and the relevance were identified, and research questions were derived from them.

Based on these questions, the research objectives were defined in subchapter 1.3. The main objective is to create an integrated and intelligent product lifecycle that uses smart factory and smart product data to develop customisable smart product families based on generative design efficiently.

In the subchapter 2.1, “research design”, the overall structure, which is adapted from Österle’s design science research, is described.

Subsequently, the methodologies for conducting the research were revealed in subchapter 2.2. One of the main methods is the mixed literature analysis with snowballing in the analysis phase. The result of the snowballing is shown in a literature analysis network. The cause-and-effect relationships and the event-driven process chain are the methodologies for the draft phase, and an experiment is used in the evaluation phase. The results are documented in a joint master thesis and a joint scientific paper in the diffusion phase.

The limitations subchapter 2.3 highlights the limitations in addressing the research topic – these range from product properties to processes and technical properties.

In the last subchapter 2.4 the structure of the thesis is presented, which is roughly divided into the introduction, analysis (theory), draft/solution approach and validation.

Chapter 3 Current state of research

This Chapter 3 describes the theoretical basis for the development of a product lifecycle for smart customisable product families. This starts by describing the current developments in the industrial environment. Industry 4.0 is placed in the overall context, and technologies are presented. In particular, but without limitation, the technologies of mass customisation and smart products, which are the background to smart customisable product families, are also presented here. A research gap was identified in the development of these product types. The topic of product lifecycles is then analysed. Here, the product lifecycle is defined and classified into other business processes. Following this, product lifecycles represented in the literature are analysed and evaluated according to criteria that are based on the research problem.

Finally, generative design – the automation technology of construction – is presented as a possible technology for increasing efficiency in product lifecycles. The methodology and its procedure are explained to build a basis for the creation of cause-and-effect relationships in the following Chapter 4.

3.1 Industry 4.0 and smart factories

In this subchapter 3.1, the theoretical basis of Industry 4.0 and smart factories, as well as their technologies, are described. The subchapter 3.1 contains the description of the four industrial revolutions, technologies of Industry 4.0, RAMI 4.0, further developments and trends, challenges, the digital twin and data in a smart factory.

3.1.1 The four industrial revolutions

"Industry 4.0" was first introduced as the name of a future project at the Hannover Messe 2011. It is also known by other names, such as "Industrial Internet" in the US, "Industrial Value Chain Initiative" in Japan, or "Made in China 2025" in China (Dafflon et al., 2021, p. 2395). It is supposed to follow the previous industrial revolution as the Fourth Industrial Revolution. Over the years, the term "industrial revolution" has continued to shape itself and can be defined as the integration of technologies which transform how operations operate (Trotta & Garengo, 2018, p. 113).

The First Industrial Revolution started with the mechanisation of production tools (e.g., weaving looms) powered by steam power. Companies wanted to produce larger quantities to gain more profit. As a result, mass production became more popular and caused the Second Industrial Revolution to establish.

The Second Industrial Revolution was also marked by Henry Ford, the founder of the company Ford, which developed production concepts with an assembly line, thereby increasing efficiency.

The central part of the Third Industrial Revolution was the invention of the computer. Computers made it possible to automate workflows and processes.

(Oztemel & Gursev, 2020a, p. 128) describes Industry 4.0 as a methodology that transforms manufacturing from a machine dominant to a digital manufacturing process. The leading technology that makes up this revolution is the connection of machines and objects via, for instance, cyber-physical systems and the Internet of Things.

3.1.2 Technologies of Industry 4.0

Examples of Industry 4.0 technologies are big data, the Internet of Things, augmented reality, simulation, autonomous robots, and cloud services. These technologies enable the transformation of production systems and products into cyber-physical systems (Trotta & Garengo, 2018, p. 113). Cyber-physical systems 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, pp. 9-13).

The basic components of Industry 4.0 are defined by (Oztemel & Gursev, 2020b, p. 132), among others, as follows:

- **Cyber-physical systems (CPS):** CPS are types of embedded systems that are able to integrate into digital networks and create new system functionalities as part of the virtual environment (Bergera et al., 2015, pp. 368-643). CPS consist of a network where objects and systems can communicate in a virtual environment that depicts the real world through lifelike simulations. Packed with software functionalities, CPS are able to generate input data by monitoring processes, performance, parameters, and sensors. With these data, decisions can be made, for example, for condition-based maintenance and autonomy. Furthermore, CPS own the opportunity for user interaction and interconnected communication. In general, there are three stages of CPS. The first stage contains only the storage and analysis of data and identification of the system, for example, through RFID. In the second stage, the systems are equipped with sensors and actuators with a limited number of functions. The third stage completes CPS by adding multifunctional sensors and actuators, and network compatibility (Bauernhansl, 2017, pp. 1-31; Oztemel & Gursev, 2020b, p. 141).

- **Cloud systems:** Cloud systems are online systems for storing and processing data and information. Cloud systems have an increased processing capacity compared to traditional systems. Anyone with permit rights can access up-to-date data that qualifies it to form the basis for processing big data. The system and its infrastructure are more cost-effective due to their simplicity. Data security is one of the main topics of cloud systems that must be focused on when setting up a cloud. But in most cases, the central backup of data on an encrypted cloud makes file storage more secure compared to traditional systems. Depending on the access rights, a distinction is made between a public, private, hybrid and community cloud (Oztemel & Gursev, 2020b, p. 144).
- **Internet of Things (IoT):** The Internet of Things is the networking of virtual and cyber-physical systems and items (e.g., smart products ranging from household items to industrial tools). With IoT, information between CPS and items can be transmitted (Irfana Parveen et al., 2023, p. 123). According to (Leloglu, 2017, p. 124), IoT consists of four different layers: Perception Layer (e.g., Gateways or Sensors), Network Layer (e.g., 5G or Wi-Fi), Support Layer (e.g., data storage and analytics) and Application Layer (e.g., user interface or apps) (Oztemel & Gursev, 2020b, pp. 154-156).
- **Machine to machine (M2M):** M2M means the direct communication between machines and devices. The transmission of information can be wireless and wired. An example for M2M is a sensor from device 1 (e.g., machine) that sends data it records to device 2 (e.g., another machine or central computer for analysis) which can progress it (Biral et al., 2015, pp. 1-19). The essential requirement for M2M is that the machines can communicate with each other. This is done by creating uniform languages, communication channels and interfaces (Oztemel & Gursev, 2020b, pp. 146-148).
- **Smart factory:** The smart factory differs from traditional factories by using digital technologies and autonomous systems. The production organises itself and takes over the organisation of the value-added process. It uses the data from the factory to further optimise its efficiency and quality and to become more flexible (Oztemel & Gursev, 2020b, pp. 148-151). A smart factory uses and combines Industry 4.0 technologies, thus making production more efficient, transparent, safer and smarter (Strozzi et al., 2017, p. 6572). A smart factory is characterised by a wireless network, specific technologies, a smart manufacturing process, and simulation techniques.

Within a smart factory, the manufacturing will be connected wirelessly through wireless information and communication networks with devices like RFID and sensors. Manufacturing objects are tracked and traced by a Manufacturing Execution System (MES) in real time. This system also tracks production data and malfunctions in machines.

Resources of smart factories (e.g., production facilities, robots) can be seen as autonomous organisms with the ability to adapt to different situations like new products, defects, or other problems.

Another characteristic of smart factories is the manufacturing process with the ability to efficiently produce customised mass products (mass customisation) (Strozzi et al., 2017, pp. 6581-6585).

The simulation of manufacturing processes is realised by digital twins, machine learning and artificial intelligence.

- **Big data and data mining:** One of the main components of Industry 4.0 is data. Data is one of the most valuable things in the modern world, which is generated by nearly every digital process. Therefore, the modern world has access to a huge amount of data. With data mining, meaningful conclusions can be drawn from the mass of data. A factory in which data is actively collected, analysed, and used is also called a data fabric. Gartner, known for its ‘hype cycle’ in the industry, even rates the data fabric as one of the top 12 strategic technology trends that will shape the digital business field's future (Groombridge, 2022, p. 4). The data mining technology includes tools for generating, collecting, and analysing data from multiple sources. If the data is processed and used correctly, processes can be improved at an early stage. There is a growing trend towards developing tools that autonomously perform data analysis without human assistance (Oztemel & Gursev, 2020b, pp. 153-154).
- **Enterprise resource planning (ERP) and business intelligence:** ERP is a system for planning resource demands for a foreseeable period. The system is includes data and information from different areas of the company to best plan ahead for resource demand. Also, with ERP, real-time data is analysed, and information access and transparency are increased. With business intelligence, a company's data is analysed and illustrated to get a basis for decision-making (Cabrera-Rojas et al., 2023, p. 468; Oztemel & Gursev, 2020b, pp. 156-159).
- **Augmented reality (AR) and simulation:** The term “augmented reality” has a large number of definitions in the literature. The reason for this is the various possible applications of this technology. Augmented Reality is the interface between the digital and the real world. The real existing world is expanded by additional digital information, elements and animations. In (AR), digital graphic components are overlaid with the real world. From a technical point of

view, Azuma defines AR as a combination of virtual and real environments with partial overlay: “AR is about augmenting the real world environment with virtual information by improving people’s senses and skills. AR mixes three-dimensional virtual characters with the actual world in real time” (Azuma, 1997, p. 2).

Milgram and Kishino sort the different realities shown in Figure 6 by having the real environment on one side and the virtual environment on the other. The area in between is called mixed reality and ranges from augmented reality to augmented virtuality (Milgram & Kishino, 1994, p. 1321).

Figure 6: Milgram's Reality-Virtuality Diagram (Milgram & Kishino, 1994, p. 1321).

The technologies around AR are applied in various ways with regard to Industry 4.0. For example, augmented virtuality is used for product and production planning. Products or the entire production system are simulated in such a way that, with AR glasses, it feels as if one is currently in reality. This enables it to evaluate dimensions and measurements much better than drawings. A use case, for instance, is preventing errors that could be seen in advance. Another application of AR is the display of information for production employees. The application can be used for training, quality control, logistics, maintenance, remote assistance, and many other areas. The advantage is that information can be displayed in relation to objects, reducing the potential for errors, and that the hands are free physically when using AR glasses (Oztemel & Gursev, 2020b, pp. 151-152).

- **Virtual manufacturing (VM):** Initial VM developments included designing and testing production equipment and machines. This was expanded over time so as to be able to test processes and products. Nowadays, VM offers a suitable possibility to fully develop and test entire production facilities. VM can be used to model production facilities and thus to also test the manufacturability of products in virtual environments (Oztemel & Gursev, 2020b, pp. 159-160).
- **Intelligent robotics:** Robots are continuously being further developed and can thus be used in additional applications. The computing power of controllers is increasing, which means that artificial intelligence can be used. An example of this is to increases the quality, efficiency and effectiveness of automation tasks. Furthermore, robots can use artificial intelligence in conjunction with sensor technology to recognise components and determine components'

positions. This also facilitates machine-human interaction and reduces the risk of human error. Not only has the control of robots improved in recent years, the manipulators, sensors and the shape of the robots have also been further developed. For example, there are lightweight robots and autonomous mobile robots (Khorasani et al., 2022, p. 1469).

3.1.3 RAMI 4.0

RAMI 4.0 is a reference architecture model for Industry 4.0. It is intended to provide an overview of the essential building blocks of Industry 4.0. It thus creates a common understanding of standards, norms and Industry 4.0 technologies. The model has a three-dimensional structure. One of the three axes is the "Hierarchy Levels" axis. This represents the different hierarchy levels for factories and plants from the IEC 62264 standard, which forms standards for the integration of company IT and control systems. The lifecycle of products and plants is mapped on the "Life Cycle & Value Stream" axis. The "Layers" axis describes the IT representation of a machine in layers (Hankel & Rexroth, 2015, pp. 1-2).

3.1.4 Further developments and trends

Industry 4.0 technologies have already brought about many improvements in companies in recent years. The improvements range from increased efficiency to mass customisation, which is intended to enable the mass production of customisable products at mass prices. Now that the first technologies have been developed and tested, the following trends are emerging for the future (Lu, 2021, pp. 14-15):

- **Standards:** When the term Industry 4.0 was created and the first technologies started to be developed, isolated solutions were created that were not based on almost any standard. Companies also exploit this lack of standards in order to be able to sell all of their products. To be able to use different systems, machines, sensors and other Industry 4.0 components together and to achieve the most significant possible benefit, initiatives are now being created to standardise Industry 4.0 technologies.
- **AI-relevant process and system improvement & management:** Data processing and evaluation play a significant role in Industry 4.0. For example, sensors, ERPs and production systems allow a large amount of data to be collected, but often no computer-generated conclusions can be drawn from it. If comprehensive standards allow data to be collected from the entire production system, then artificial intelligence can be used to monitor the parameters

and continuously improve the system holistically.

- **The cooperation of humans and robots:** Whereas robots had to be hidden behind protective fences in the past, they can now work together with humans if they are equipped with the necessary sensor technology and certification for this purpose. This is made possible by new types of force sensors and protective skins that recognise humans. Through the cooperation of man and machine, manufacturing processes and quality can be optimised, and ergonomics improved. A distinction is made between different degrees of interaction, ranging from coexistence, synchronised, cooperating and collaborating (Bauer et al., 2016, p. 9).
- **5G:** To be able to use data-sending devices everywhere, wireless technologies are required. With 5G, a standard for networks and network functions has emerged that can also be used for Industry 4.0 technologies. With 5G, a fast, real-time, mobile, and secure IoT can be implemented, accelerating companies' digital transformation (Lu, 2021, p. 15).

3.1.5 Challenges

Challenges for Industry 4.0 are issues in security, educational, interoperability, Digital Twins, infrastructures, human-machine cooperation and ethical aspects.

- **Security:** Through networked devices, data storage in a cloud and remote maintenance, there are many possible risks for cyberattacks. Until now, it was not possible to access production equipment outside the factory premises, but now it is possible to access the machines from anywhere in the world. In the event of a cyberattack, production facilities can fail for an extended time, resulting in high costs and even endangering human lives through remote control. This means that machine manufacturers need to have the competencies to plan and implement strategies for the cybersecurity of machines and systems. An active risk management to avoid cyberattacks is proposed by (Hajda et al., 2021, pp. 3-7). (Ferencz et al., 2021, p. 245) proposes to bundling these competencies in a Security Office Centre (SOC) and creating a responsible department that monitors the security of the devices, centrally managing corporate security and able to react to threats in real-time. The main tasks of the SOC are to integrate smart devices into the industrial system, manage a platform for security information and event management, identify and control vulnerabilities in the system, and perform preventive steps to minimise the vulnerability (Ferencz et al., 2021, pp. 245-247).
- **Education/Training:** To successfully implement Industry 4.0 technologies, companies need competent personnel (Karadayi-Usta, 2020, pp. 973-978). The required skills are currently in great demand which results in difficulties for companies to find suitable employees. Many of

these job types (e.g., big data analyst) did not even exist ten years ago (Leopold et al., 2018). For this reason, companies need to provide training to enable their employees to learn new necessary skills (Leitão et al., 2020, pp. 304-305).

- **Interoperability:** As described in section 3.1.4, "Further developments and trends", the standardisation of machines, interfaces and networks is a trend and currently a challenge for companies. In order to successfully use Industry 4.0 technologies, all devices and systems must be able to interoperate and communicate with each other (Leitão et al., 2020, pp. 305-306).
- **Digital Twins:** The most significant challenges of digital twins technology are based on the previous challenges. These challenges include the use and correct analysis of big data, as well as the creation of the necessary infrastructure for digital twins. This infrastructure makes the successful and realistic simulation of products and production facilities possible in the first place. To use the data, systems must be standardised, and a cyber security concept must be in place to prevent the loss of secret company information (Leitão et al., 2020, p. 306).
- **Processing and communication infrastructures:** For the success of Industry 4.0, a high-performance infrastructure is necessary, via which data can be communicated and used. This also includes data centres for storing and processing these data packets (Leitão et al., 2020, pp. 306-307).
- **Human-machine cooperation:** Humans have the most flexible role in a smart factory. Therefore, collaboration between automated robots and humans is an important task. The correct use of human capacities in cooperation with machines is a challenge. A distinction is made between using humans as human-in-the-loop (HitL) or human-in-the-mesh (HitM). With HitL, the human is directly involved in the production process (e.g., quality control). With HitM, the human is used as a production planner. Especially when engaged as HitL, human safety is a challenge (Leitão et al., 2020, p. 307).
- **Ethical aspects:** As the shift to Industry 4.0 changes people's working conditions, many ethical questions need to be answered. For example, automation is replacing jobs, and Big Data and sensors can be used to monitor the performance of individual employees. Industry 4.0 will create areas where employees are needed and others where employees are replaced by robots. Including the individual human being in this workforce, transformation is an important task that will have a significant impact on the success of Industry 4.0 (Leitão et al., 2020, pp. 307-308).

3.1.6 Digital Twin

Depending on the focus of the research, there are different definitions of Digital Twins. A general definition is that the Digital Twins consists of an intelligent combination of a unique instance of a universal digital template model and the individual digital shadow (Stark, 2017, p. 1). A Digital Twin is a coupled virtual representation of physical assets, which makes the data provided by the physical object useful for several use cases. The Digital Twin virtually represents products, processes and the whole production system. Another definition of the term "Digital Twin" is given by (Kunath & Winkler, 2018, pp. 225-231): "The Digital Twin of a physical object [is] the sum of all logically related data, i.e. engineering data and operational data, represented by a semantic data model."

Digital twins support, on the one hand, the development, and, on the other hand, the use of a product through simulation. In addition, another area of application has also been seen during recent years in product lifecycle management. This means that digital twins can be used in all phases of a product lifecycle within the areas of the product concept, design, development, production, transport, sales, commissioning, after-sales, and recycling (Klostermeier et al., 2020, p. 4).

3.2 Smart customisable product families

The development of smart customisable product families is part of the research goals. Therefore, smart products, mass customisation and customisable product families are described in this section 3.2.

3.2.1 Smart products

Generally, a smart product has most of the following features: It has a unique identity, it communicates with the environment, it stores data relating to itself or the environment, it uses a language to represent properties (e.g., production requirements), and it has a (partially) autonomous decision-making function (Raff et al., 2020, p. 385; Wong et al., 2002, p. 7).

Smart objects can be classified into different classes based on their software and hardware capabilities. The classification based on (Raff et al., 2020, p. 392) is shown in the following Figure 7.

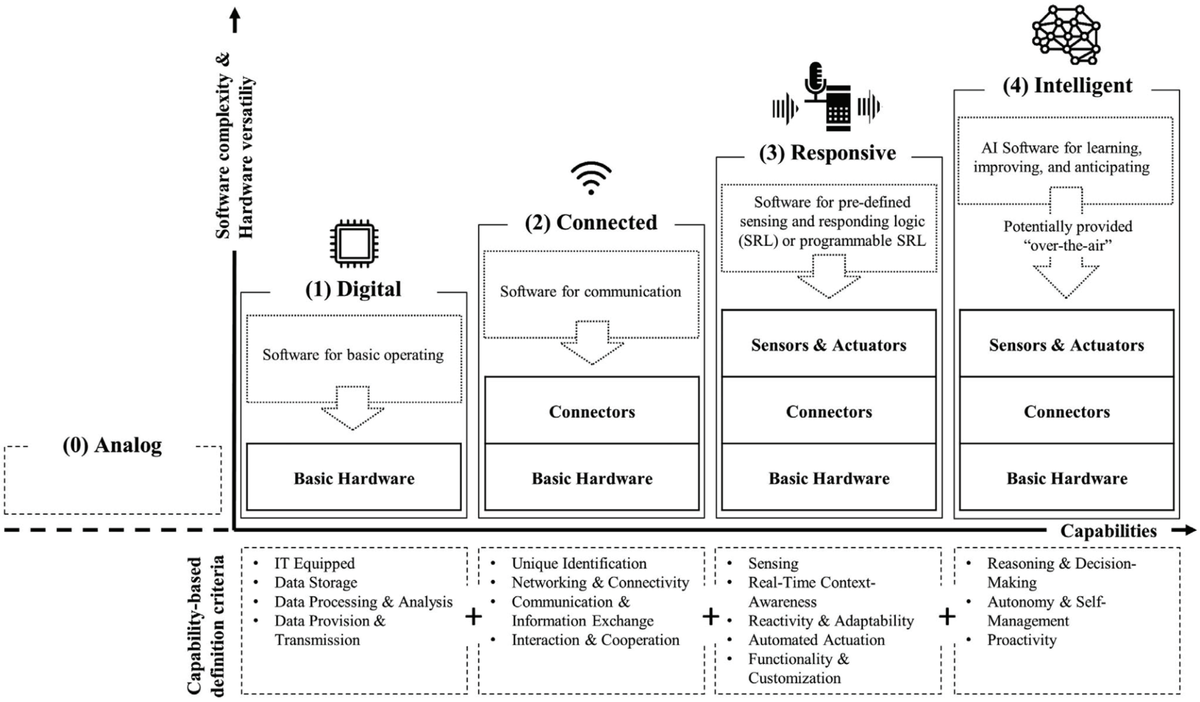


Figure 7: Framework of Smart Product Archetypes (Raff et al., 2020, p. 392).

Starting with the "(0) Analogue" class, additional properties are added at each stage.

The first class after analogue products are digital products. These are characterised by the fact that they have basic hardware and software for basic operation. They are equipped with IT, have a storage space, can use, and analyse data and provide and transmit data.

The second class, "(2) Connected", is characterised by the fact that it also has connectors. It also has a unique identification, can interact in the network, connect, and communicate with other devices, and exchange data and information.

In the third class, "(3) Responsive", the products are equipped with sensors and actuators. This enables the products to react to circumstances and act automatically. Furthermore, they have predefined programmes to sense and respond.

In the fourth and final class, "(4) Intelligent", the products have the ability to learn and improve with the help of artificial intelligence. They can draw conclusions from situations and react to them. The products are autonomous and can manage themselves proactively (Raff et al., 2020, pp. 391-397).

For this research, the product has to be at least in the third stage. This is because the product has to be connected to the network to send sensor data during production and use.

3.2.2 Mass customisation & customisable product families

Mass customisation means the automated manufacturing of bespoke products (Kull, 2015, p. 1). The term was first defined by (Pine, 1993a, p. 47) saying that mass customisation is the "development, production, marketing and delivering of affordable goods and services with enough variety and customisation that nearly everyone finds exactly what they want". The intention is to build individual products with lot size one on a large scale at costs of mass products (Thomassen & Alfnes, 2017, p. 27). It differs from mass production in the aspect that the mass products can be customised. Moreover, mass customisation differs from mass configuration due to the fact that in configuration there is a set of solutions in advance, which the customer can choose from, whereas in customisation, the number of possible solutions is unlimited. In order to implement mass customisation, fundamental changes in the company are necessary. These concern business processes in development, production, sales, and after-sales processes.

For mass customisation a combination of technologies from digital manufacturing and smart factories is necessary. The concept offers new business models with the individualisation of products and customers receive an individualised product, which corresponds exactly to their needs.

The requirements for mass customisation can be viewed from two sides. Looking at the internal view of the company, mass customisation capabilities need to be built. These include, for example, the development of components in solution spaces, robust process design and selection navigation. Looking at the external view of the company, the basic requirements can be divided into technological progress and market demand. For example, new production and development technologies, as well as automation, play a major role in technological progress. Regarding market demand, as mentioned in the section 1.2 "Research problem statement and questions", an increased demand for individualisation of products can be observed (Wabia et al., 2020, p. 163).

The types of mass customisation can be sorted into different categories. (Gilmore & Pine, 1997, pp. 1-8) have fundamentally classified the sales types of mass customisation based on the change of the product and its representation. The four approaches are shown in the following Figure 8.

When the product and its representation change, the customisation can be classified as *collaborative customisers*. The company enters into dialogue with its customers in order to design exactly the right product. This approach is relevant for customers who need a lot of consultation when creating the product. In the case of *adaptive customisers*, a standard product is set as the basis, which the customers can subsequently configure themselves. With *cosmetic customisers*, a standard product is presented differently to customers but can be used in the same way. *Transparent customisers* sell the customer an individual product without the customer knowing that it is tailor-made for her or him (Gilmore & Pine, 1997, pp. 1-8).

However, often in some instances not only one approach fits, but a mixture of different approaches is useful.

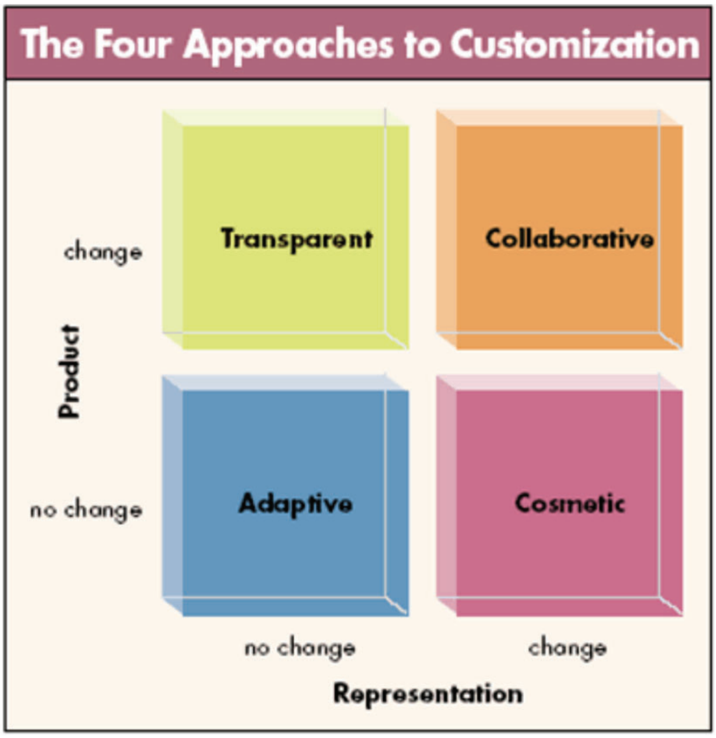


Figure 8: The four approaches to customisation (Gilmore & Pine, 1997, pp. 1-8).

According to (Hu, 2013, pp. 3-8), a large variety of products can only be implemented if the production system is reconfigurable and the product is based on a product family architecture.

In customisable product families, a range of products is derived from a standard product platform to meet different market applications (Gauss et al., 2021, p. 256; Meyer & Lehnerd, 1997).

The main characteristics of product families are that the products can be customised while having a uniform basis. Thus, the product is a variant of the product family. The product is defined on the basis of the parameters of its product family and the product family description. The difference from conventional products, however, is that the focus of the product definition should be the individual customer specification. Another characteristic of product families is that there are complex internal relationships between the generations in the development of a subsequent generation. This is the case because there is a much larger solution space for the products (Pan et al., 2014, p. 869). According to (Shao et al., 2012, pp. 2612-2614), the end of product families cannot be predicted.

It requires an advanced information and data management system as product families play an important role in mass customisation, and interrelationships become more complicated due to the interfaces in and between individualised products and the product family. Because information is heterogeneous and depends on the generation and variant of a product, it is complicated and time-consuming to make it analysable and usable as a whole for all phases of the product lifecycle. However, to improve product properties and the efficiency and effectiveness of processes around the product families, it is imperative to use the data and information from the entire lifecycle (Huang et al., 2007; Pan et al., 2014, pp. 869-870).

3.3 Product lifecycles

In this subchapter the terms product lifecycle and product lifecycle management are defined. Afterwards, the main phases of product lifecycles are described. In the following sections product lifecycles are classified and differentiated from other business processes. Then the lifecycle design is characterised. After building this basis requirements for reference processes are defined, and reference processes are presented and evaluated.

3.3.1 Definition of product lifecycle

The product lifecycle refers to the phases a product goes through in its lifespan, and it is the subject of product lifecycle management (Stark, 2022, pp. 1-32). The definition and the main phases are described in this section. Furthermore, a differentiation is made from other business processes and the lifecycle from marketing point of view. The final part describes the lifecycle design.

3.3.1.1 What is the Product Lifecycle?

The lifecycle of a product ranges from the initial product idea, through conception, development, production and use, to the point at which the product becomes unusable and is disposed of (Stark, 2022, pp. 1-32). Other sources declare that the start of a product lifecycle is marked by the recording of customer requirements and the end is reached when the product is disposed of (Pan et al., 2014, pp. 869-886).

3.3.1.2 Product Lifecycle Management

In product lifecycle management, the entire lifecycle of a product is managed (Duda et al., 2022, pp. 171-185). The product lifecycle management is increasingly influenced by smart products and smart factories due to new possibilities with data analysis (Zhang et al., 2019, p. 6758).

3.3.1.3 Main phases of product lifecycles

There are different definitions for the main phases of a product lifecycle. Consistently, these always include the phases beginning of life, middle of life and end of life. (Stark, 2011, pp. 1-2) defines the main phases of a lifecycle as shown in the following Figure 9.

Beginning of Life			Middle of Life	End of Life
Imagine	Define	Realise	Support/Maintain/Use	Retire/Dispose

Figure 9: The five phases of product lifecycles and BoL, MoL and EoL based on (Stark, 2011, p. 2).

In his theory, product lifecycles have five phases. It begins with the imagine phase, in which an idea is generated. This is followed by the define phase, in which the idea is defined and linked to objectives. Afterwards, the realisation of the idea in the realise phase takes place. Once the idea has been realised, the utilisation, maintenance and support phase follow. The retire/disposal phase builds the end of a product lifecycle when the product becomes unusable.

(Ding et al., 2022, pp. 1641-1642) define the product lifecycle as shown in the following Figure 10.

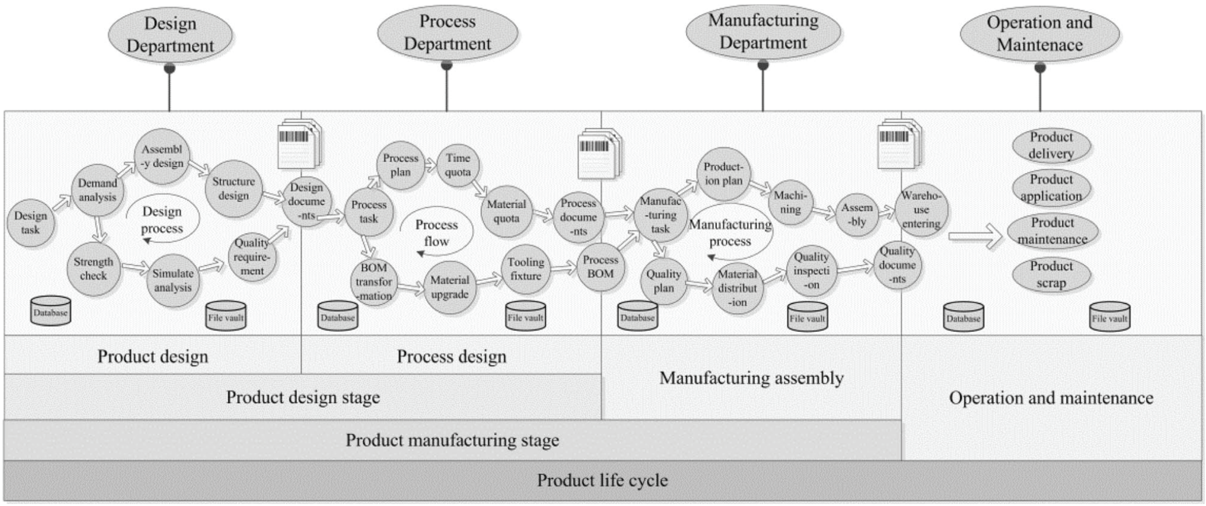


Figure 10: Product Lifecycle (Ding et al., 2022, p. 1642).

According to (Ding et al., 2022, pp. 1641-1642), the product lifecycle starts with product design, in which, among other things, the product, the assembly and the structure are designed, and parameters are defined and simulated. Within this phase, the design department essentially assumes the leading function. After the product design has been created, the process design follows. This is essentially the plan of how the product will be manufactured. This includes work steps, process plans, bill of materials (BOM) and tool production. Product design and process design are the superordinate product design stages. The third phase is manufacturing assembly. This includes all the tasks for manufacturing and assembling the product, as well as its distribution and quality documents. The product manufacturing phase is superior to the product design phase and the manufacturing assembly. The final phase is operation and maintenance. This includes, among others, the product's delivery, use, maintenance and disposal.

In the context of this work, the product lifecycle is divided into six main phases, namely; (1) pre-development, (2) product engineering, (3) process engineering, (4) production, (5) use and (6) end-of-life:

1. Pre-development includes product and project definition, product strategy and the definition of organisational roles (Khurana & Rosenthal, 1998, p. 61). These activities can be realised according to (Costa & Toledo, 2016, p. 715) with the phases opportunity identification, opportunity selection, idea generation, idea selection, concept development, concept selection and project planning.
2. Product engineering includes the design of the product in terms of assembly design, structure design, construction and much more (Ding et al., 2022, pp. 1641-1642).
3. In process engineering, the manufacturing process is planned, and production plans are drawn up. In addition, tools are manufactured (Ding et al., 2022, pp. 1641-1642).
4. In the production phase, the product is manufactured and assembled. In addition, the quality of the product is checked before delivery to the customer (Ding et al., 2022, pp. 1641-1642).
5. In the use phase, the product is delivered to the customer and users. In the process, it is also maintained and repaired (Ding et al., 2022, pp. 1641-1642).
6. In the end-of-life phase, the end of the product is reached. It can then either be restored, recycled or disposed of (Stark, 2011, pp. 1-2).

3.3.1.4 Classification and differentiation from other business processes

A product is not created by one step but by many small steps of a product engineering process. The product idea, which emerges from the market, is developed into a product ready for production with the product engineering process, which is divided into many different processes. These processes are generally similar but differ in detail between companies and product types. Processes consist of several working steps (Feldhusen & Grote, 2013b, p. 11). The product engineering process is often associated with the product lifecycle. To make the differences visible, the two processes are compared below.

A product engineering process describes a predefined methodology to control and manage product development activities. It includes the complete realisation cycle of a product from the idea through the various development stages to the marketable product (Raff et al., 2020, p. 385; Wong et al., 2002, p. 7). According to (Browning et al., 2006, p. 114), "product development is an endeavour process of multifunctional activities between defining a technology or market opportunity and starting production" (Albers et al., 2016, p. 2). According to (Albers et al., 2016, p. 2), product engineering includes not only product development, but also the development of the production system and processes and other activities throughout the product lifecycle that influence product development (e.g., sales and disposal). In order to break down a problem, to develop solutions in parallel depending on expertise, and bring them together to form an overall solution, higher-level coordination of tasks is necessary.

In the following Figure 11, the product engineering process is compared with the product lifecycle.

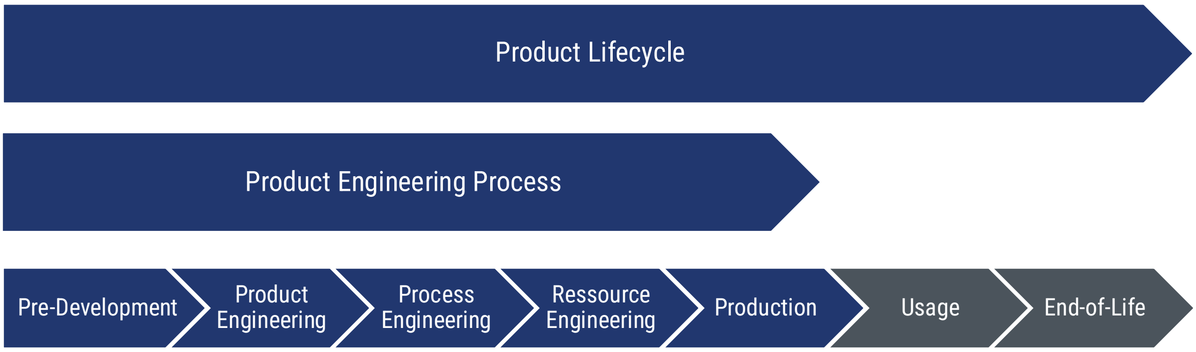


Figure 11: Product Engineering Process and Product Lifecycle comparison based on (Haußmann, 2012, p. 2).

The product engineering process ends when the product is marketable. This is illustrated in Figure 11 from the phases highlighted in blue. In addition, the product lifecycle includes the phases of marketing the product, use, after-sales, and disposal of the product.

3.3.1.5 Distinction from the product lifecycle in the marketing field

From a marketing point of view, a product also has a limited lifespan and goes through different stages during this time. According to this marketing perspective, it is divided into four stages, and each stage presents a different challenge to which the marketing mix responds. The four stages are launch, growth, maturity and decline (Steinhardt, 2010, p. 80). The product lifecycle model and its stages are shown in the following Figure 12 with time on the horizontal axis.

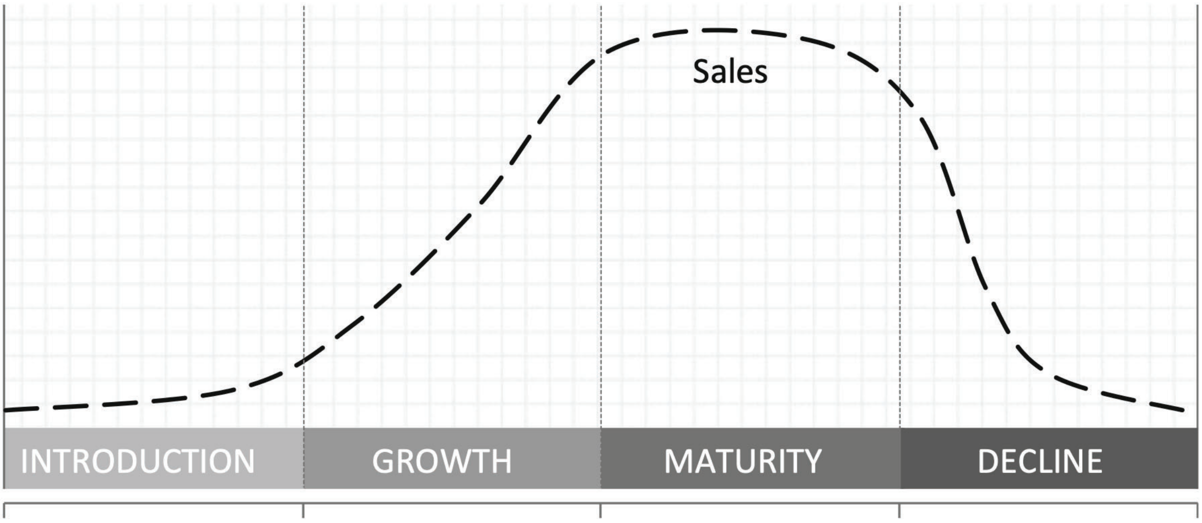


Figure 12: Product lifecycle model stages in business administration (Steinhardt, 2010, p. 80).

Significant differences can be seen if one compares the product lifecycle as a business administration model with the phase model from the creation to the disposal of products. The product lifecycle as a business administration model only considers the period in which the product is sold, i.e., from market launch to end of sale. The product lifecycle as a phase model, however, also includes the previous and subsequent phases and thus covers a much more extended period of time. It has more technical topics such as the development of products and their disposal.

3.3.1.6 Lifecycle Design

Lifecycle design is when the product is developed based on requirements imposed by all phases of the product lifecycle. These requirements can be, among others, technical, economical, and environmental. The aim is to create products that perform well in every phase of the product lifecycle and not only in the production and use phase. The focus in lifecycle design often lies more on the end-of-life strategies than in other phases (Niemann & Pisla, 2021, p. 20).

3.3.2 Requirements for the reference process

As described in Section 1.2 “Research problem statement and questions”, there is a need to create a comprehensive product lifecycle for the development and production of customisable smart product families with different variants.

The requirements for the comprehensive product lifecycle are derived from the input and output factors of the product lifecycle, which are presented in the following Figure 13.

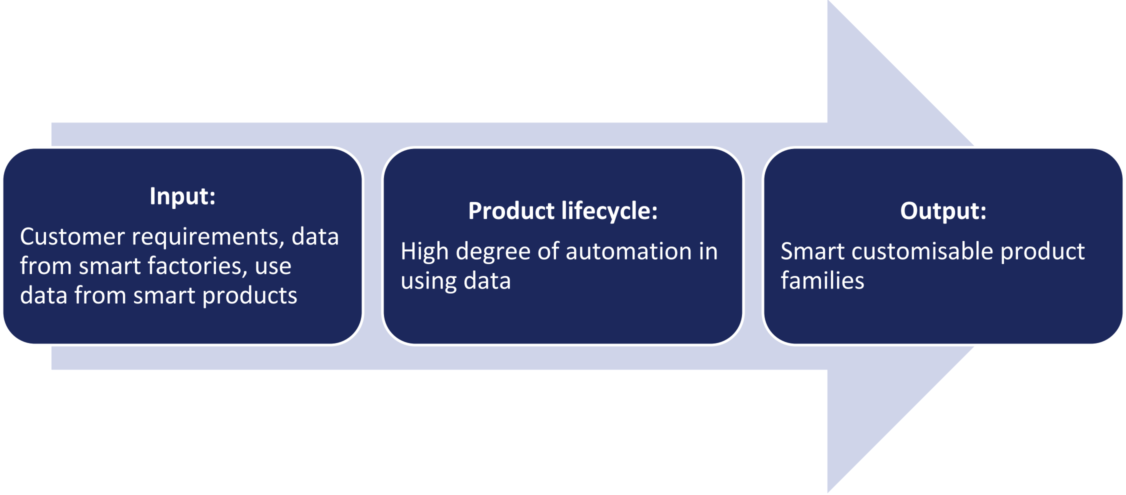


Figure 13: Input and output factors of the comprehensive product lifecycle.

To find a suitable reference process for the research problem, requirements for the reference process must be defined first. The reference process is intended to provide a basis framework of current product lifecycles used in the industry. With the help of the knowledge gained from the reference processes a comprehensive product lifecycle should be defined. It will be based on a combination of the reference processes with further optimisations.

Since the focus is on optimising the development of products, product engineering processes, which can be used as part of the product lifecycle, were mainly collected and analysed from the literature. The focus is on engineering, as product requirements from previous product variants and generations are incorporated into the design and definition of new products, and the development of smart customisable product families is the core of the research problem.

In order to address the research problem as accurately as possible, the following requirements are set as criteria to evaluate the reference processes:

- The product lifecycle should take into account the development of modular product structures or product families.
- The processes of the product lifecycle should not be designed for products with only one generation, but for products with several generations. This is to be considered as over 80 % of the products are offered in generations (Albers et al., 2014, p. 2).
- The product lifecycle takes into account the comprehensive development of an individualisable product family or smart products with their external and internal diversity.
- The smart products are produced in a smart factory and have at least the smart product archetype class three (responsive).

The defined requirements are not expected to be fully met by any product lifecycle. However, they are used to search for processes with a focus on these requirements. As a result, the next step is to describe different product lifecycles and development processes and to check which requirements they fulfil. Based on the evaluation, the reference processes that fulfil the most requirements are selected.

3.3.3 Reference processes

There are many concepts for product lifecycles and engineering processes in the literature. How a product lifecycle or product engineering process is laid out often depends on the product and the industry. Products with highly complex electronics need to be developed differently than products with simple mechanics. Therefore, a wide range of product lifecycles and engineering processes exist. Most of the processes in the literature are for developing only one product generation without any variants. This addresses only indirectly the challenges that arise in the development of intelligent product families. In addition, the literature rarely describes methods for using data from production. This section aims to get an overview of the most common product lifecycles and product engineering processes and how to use them for research.

3.3.3.1 VDI 2221: Methodology for Developing and Designing Technical Systems and Products

VDI 2221 is a basic process description of the Association of German Engineers (VDI). The procedure is divided into seven steps as shown in the following Figure 14.

The first step of this procedure is to clarify and specify the development tasks. After that, functions and their structures are to be determined. Based on that, solution principles, and their structure are sought. These solution principles are structured in the next steps in realisable modules. Those elementary modules are designed afterwards. Whilst having separate modules, they are combined into the complete product. As the last step, the execution and use information is worked out (Krause & Gebhardt, 2018, pp. 245-247).

The described procedure can be used as a general procedure for practice. Nevertheless, it is only suitable for products without modular product structures and with one generation and no variants. Moreover, it is also not suitable for complex and smart products. It also offers only rough development steps and no exact processes. Furthermore, it is not designed to develop products that are produced in a smart factory.Based on this, VDI 2221 cannot be used as the primary reference process.

Only the basic process steps in the construction phase can be used as input.

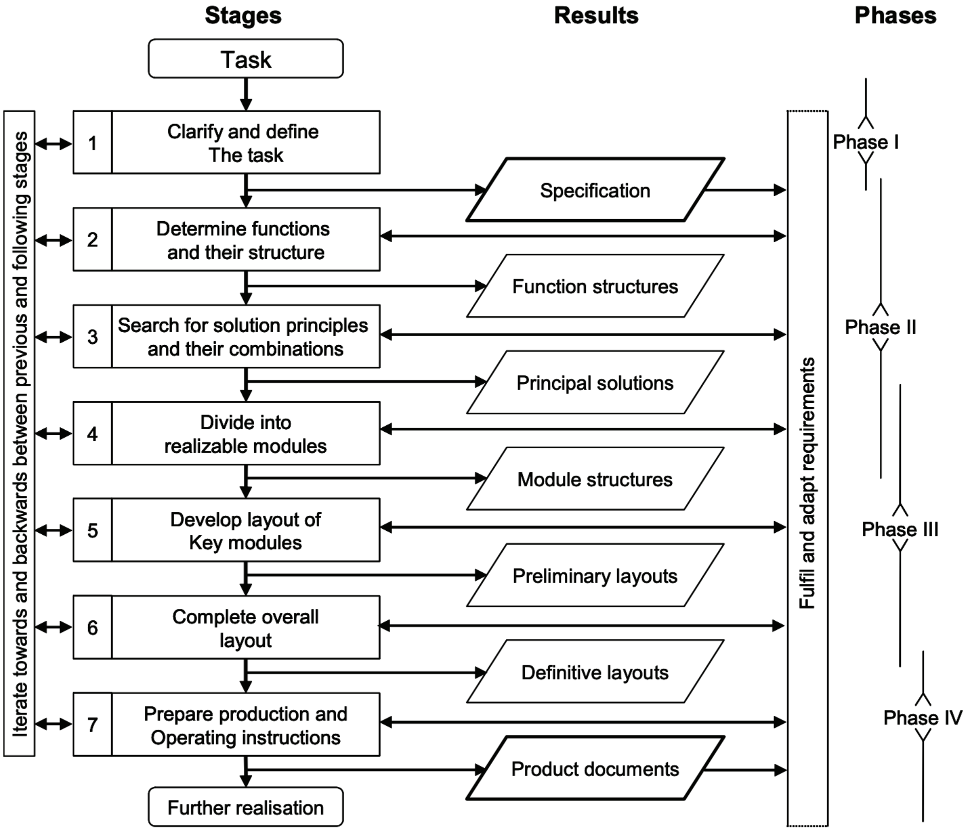


Figure 14: Systematic approach to the development and design of technical systems and products VDI 2221 (Jänsch & Birkhofer, 2006, p. 49).

3.3.3.2 Integrated Product engineering Model (iPeM)

The integrated Product engineering Model (iPeM) is a generic meta-model that was first introduced by (Albert & Mirko, 2007, pp. 1-9) with the integrated product development process management model that was based on systems engineering and systematic problem-solving. Since then, it has been continuously developed through application and feedback from research and practice. It builds on the main steps of VDI 2221 (Albers et al., 2016, p. 1). The model is shown in Figure 15.

This model has better usability through a phase model and a designation of a system of objectives, a system of resources and an operation system. The interaction of these three systems is called system triple of product engineering by (Ropohl, 1975).

In the system of objectives, all requirements and objectives of the product are specified. These also include dependencies, interrelationships, and boundary conditions. To ensure that the target system applies entirely to the product at the end of a development process, there is the system of operation, which lists the activities, methods and processes necessary to achieve the target. A distinction is made between micro (repetitive activities) and macro activities (areas of product development). (Albers et al., 2016, pp. 2-3)

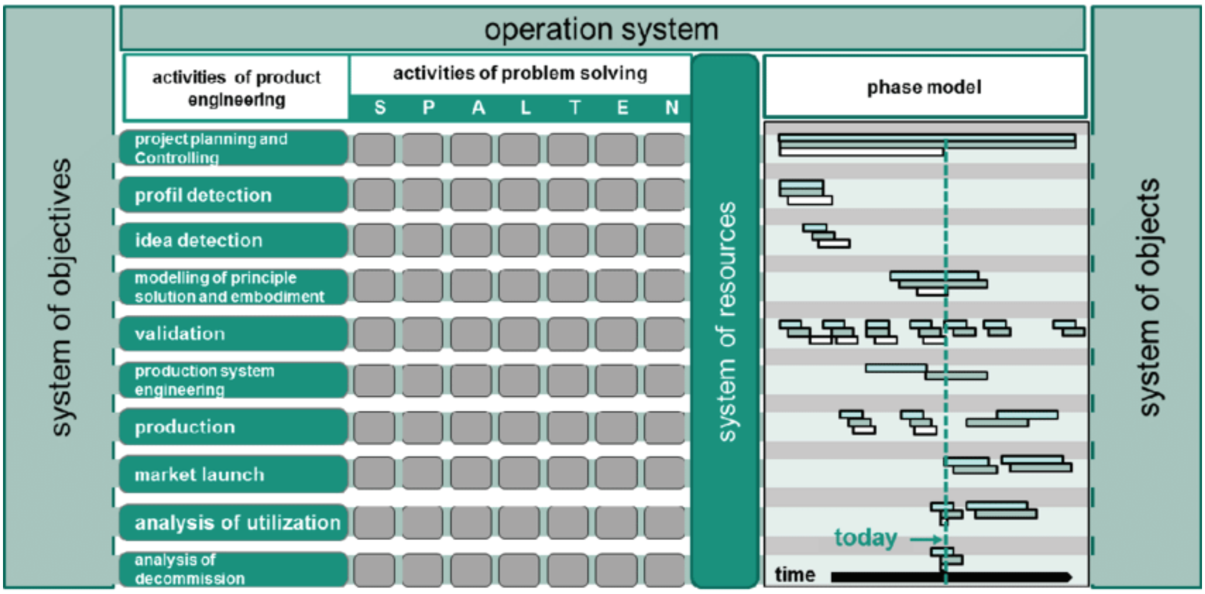


Figure 15: Integrated Product engineering Model (Krause & Gebhardt, 2018, pp. 247-248).

The SPALTEN (German for "to split") problem-solving process is used to deal with the micro activities. Each letter of SPALTEN stands for an activity to be carried out in the order of the letters. In the beginning, the situation is analysed (S), then the problem contained (P), and finally, alternative solutions are sought (A). From these solutions, promising ones are selected (L), the consequences are analysed (T), and a solution is decided on and implemented (E). In the last step, an overall evaluation and lessons learned are formulated (N) (Albers et al., 2005, pp. 3-7).

Macro activities include project planning and controlling, profile detection, idea detection, modelling a principle solution and embodiment, validation, production system development, production, market launch, utilisation analysis, and disposal analysis. The timing of the activities is presented in a phase model (Albers & Braun, 2011, pp. 6-25).

In order to be able to map the development of generations as well as other business and project areas, the iPeM was revised in 2016 on the basis of empirical studies and literature analysis. It is shown in the following Figure 16. In the process, the fundamentals of the model stayed the same, but the activities in the operation system were adjusted, and the model was mirrored on several layers.

The activities in the operation system are quantitative expanded and restructured in the cluster “product engineering activities” and “basic activities”. In the second adaptation, the approaches for generation development and different perspectives of product engineering are represented in layers. Each layer has exactly the same structure, but the activities can be shifted in the phase model. Each product generation and each perspective (product strategy, production system and validation system) form its own layer. The "Product" layer forms the first layer and contains the activities for the development of the product itself. Additional layers can be added per product to represent a further generation. The layer "Validation system" contains all activities necessary for the development of the validation environment. The layer "Production System" develops the production system for manufacturing the product. The "Strategy" layer deals with all business activities that ensure the long-term success of the company (Albers et al., 2016, pp. 4-5).

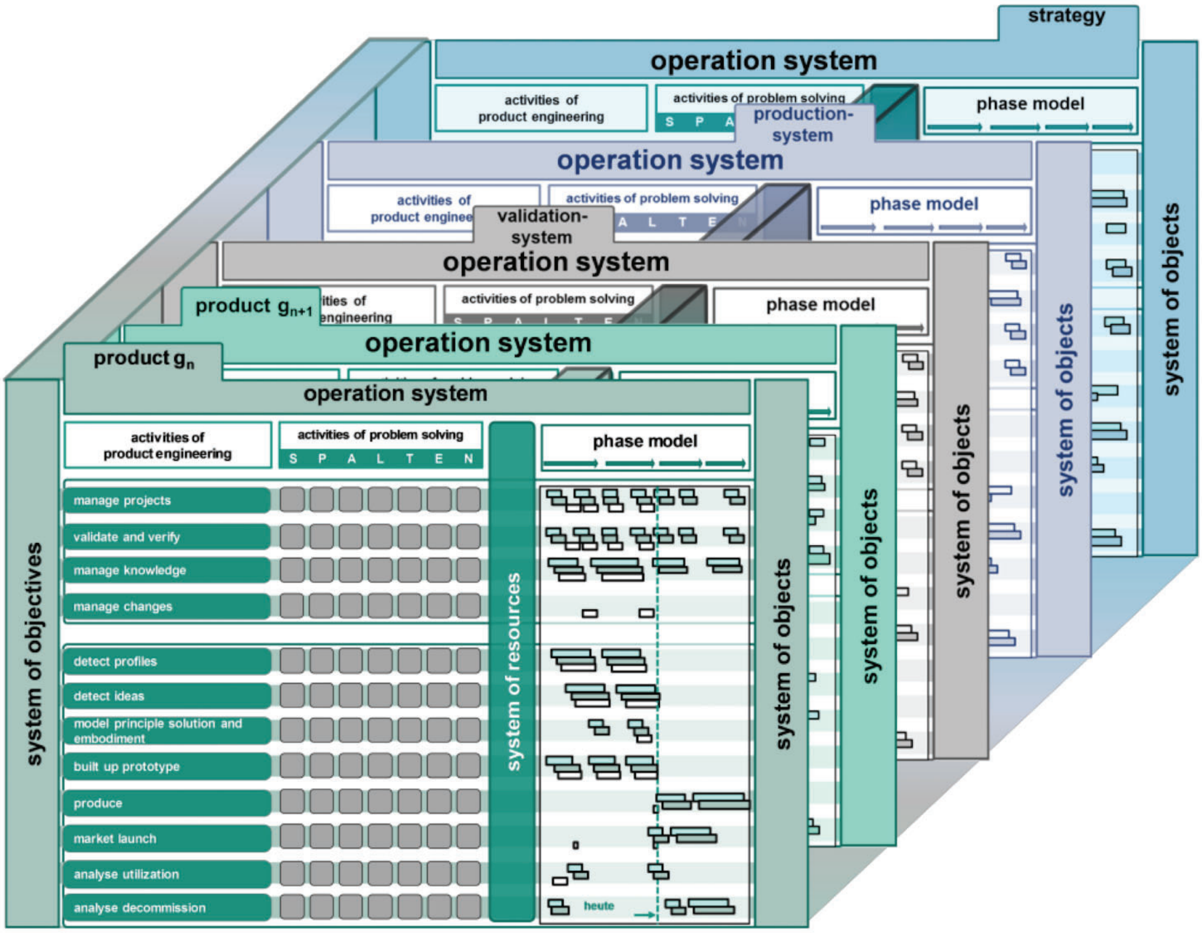


Figure 16: The integrated Product engineering Model (iPeM) in the context of product generation engineering (Albers et al., 2016, p. 5).

As with VDI 2221, iPeM does not consider the simultaneous development of multiple variants in a product family. However, this model considers the development of product generations, which allows modular product structures to be created for product variants. In addition, iPeM shows a way to develop smart production systems and embeds these development steps as a fixed layer. In this model, it is assumed that products are based on reference products and that new development never occurs due to existing production systems and employee knowledge (Krause & Gebhardt, 2018, pp. 247-248).

The iPeM can be used as a general procedure for practice with a proposal for the chronological application of the processes. It has better applicability through a phase model and application of objects, operations and resource systems. It is possible to model the entire company processes comprehensively. "SPALTEN" is a helpful method toolbox for micro activities. However, the iPeM only illustrates rough steps and, with the multiple layers, it is a complicated application.

3.3.3.3 VDI 2206: V-Model for development of mechatronic systems

The V-Model for the development of mechatronic systems is based on the V-Model of the software industry and adapted in VDI 2206. It describes the macrocycle of the development of mechatronic systems and generally needs to be executed several times to get a complete product. The different steps are shown in the following Figure 17.

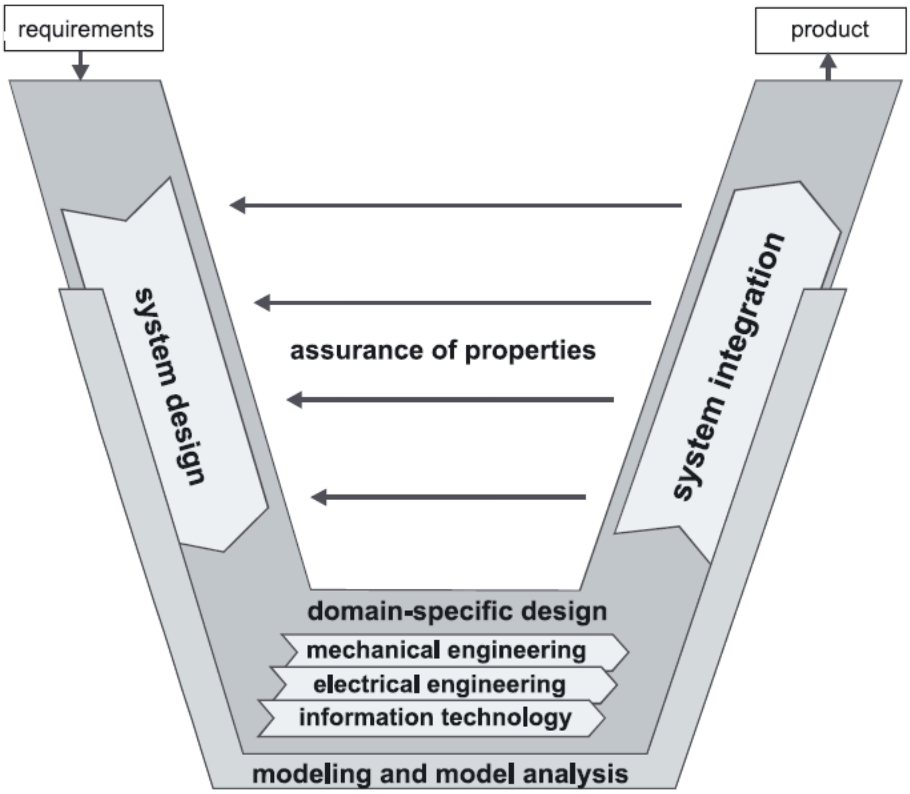


Figure 17: VDI 2206: V-Model for development of mechatronic systems (Vahid & Wang, 2017, p. 16).

In the first step, the overall requirements are broken down into sub-functions as well as their assignment of solution elements. Those solutions will be concretised within the subject area (mechanical engineering, electrical engineering, and information technology). In the last phase of the V-Model, those specific solutions are combined in the system integration phase.

The V-Model gives an excellent basis for developing smart and customisable products with a module platform due to the division of subject areas. However, the development of multiple generations is not considered. There is also a risk of failure when different developing areas do not work together due to the separation of system responsibilities. However, the VDI 2206 does not consider the development of a production system, but this is considered by various adapted V-models. An adapted V-model that takes integration into production and assembly into account during system integration is shown in the following Figure 18 (Krause & Gebhardt, 2018, pp. 248-249).

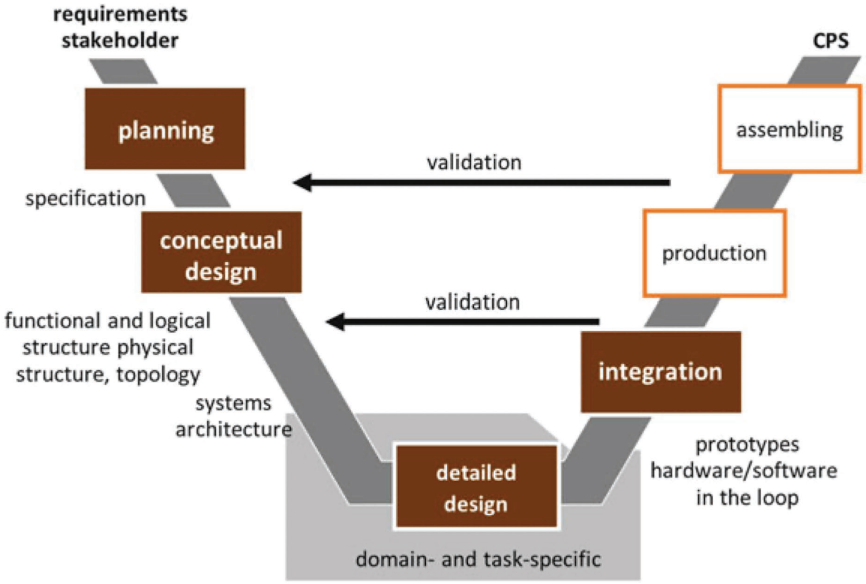


Figure 18: V-Model in the context of CPS (Biffl et al., 2017, p. 38).

3.3.3.4 Model of architecting steps

The model of architecting steps is tailored to develop products with variants and modules. The Model of architecting Steps is a generic procedure model that defines steps for the development of those products. The different steps are shown in the following Figure 19.

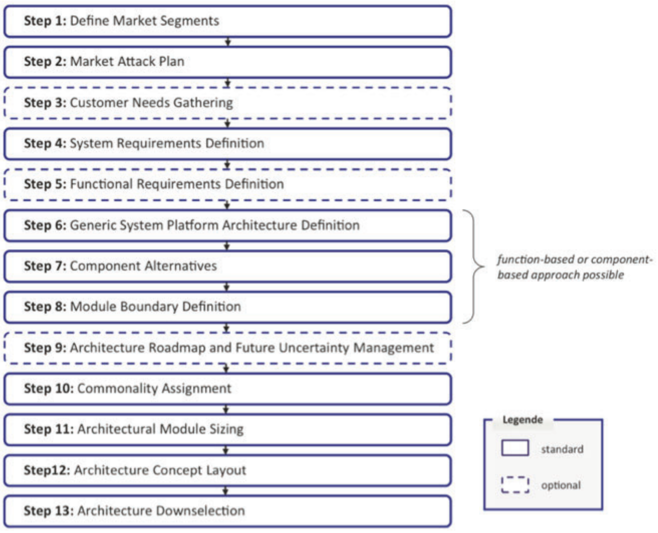


Figure 19: Model of Architecting Steps (Otto et al., 2016, p. 30).

Although the model is developed with the help of literature and companies, the lack of main development steps makes it difficult to apply in practice. Nevertheless, the model shows the overarching activities for developing modular product structures in all development phases, but does not address the development of smart products (Krause & Gebhardt, 2018, p. 249; Otto et al., 2016, p. 30).

3.3.3.5 Process for Production Planning

The production planning process according to (ProSTEP, 2010, pp. 4-14) is part of the overall product creation process. It is shown in the following Figure 20. It begins with the release of the product idea, followed by the concept development also starts. The production planning process is divided into preliminary planning (concept planning, rough planning and detailed planning) and series planning. In the first activity of production planning, the product specifications and predecessor products serve as a basis. The first work plan and production parts list are created as soon as the first product-defining data are available. The routing and the bill of materials form the preconditions at the start of production (SOP). The production planning process ends when the product is discontinued and the end of production (EOP) is reached (ProSTEP, 2010, pp. 9-10).

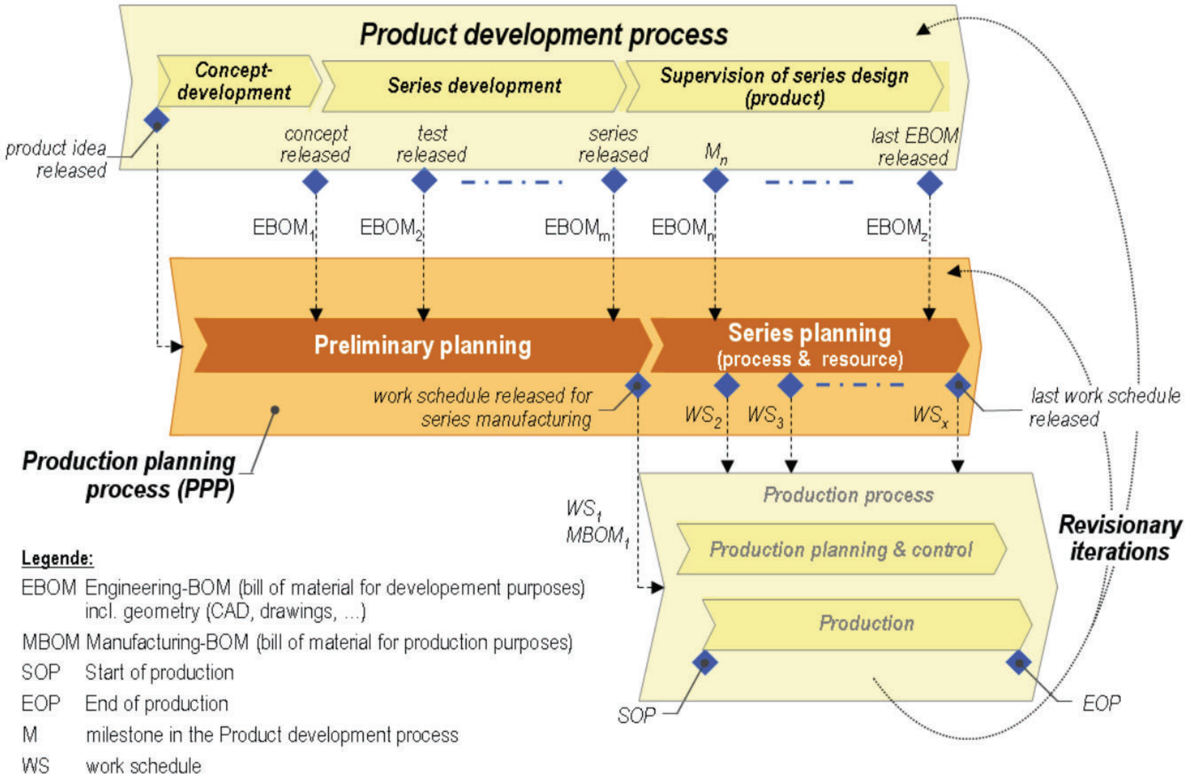


Figure 20: Production planning process (PPP) (Macke et al., 2012, p. 540).

The production planning process considers processes related to production which makes it only usable as an add-on to the reference processes. It contributes to a consistent understanding of phases and processes in the product planning process as well as the definition of interfaces and milestones. It gives a basis for a rapid implementation of products and process changes and for defining own company-specific planning processes. However, it only has a rough structure and does not consider smart modular product families with multiple generations.

3.3.3.6 Product Engineering Process by Feldhusen & Grote

According to (Feldhusen & Grote, 2013a, pp. 22-23), a product development process ranges from the planning to the manufacturing of a product. In between are the steps of development, concept development, concept design, design, and documentation. The procedure is shown in the following Figure 21.

In development, solutions are worked out, evaluated, and selected. In the next step, concept development defines the preliminary product architecture, functional scope, costs, and interfaces between different technical disciplines. This is followed by concept design, in which the product structure, main parameters of the main assemblies (e.g., design, installation space or weight) and the service and production concept are created. After that follows the design phase, in which the main assemblies are divided into components and these, including their interfaces, are then designed. When these steps have been completed, the associated processes are documented. In addition, parallel processes are running that include project, quality, risk and change management, as well as norming, procurement and production planning (Feldhusen & Grote, 2013a, pp. 22-23).

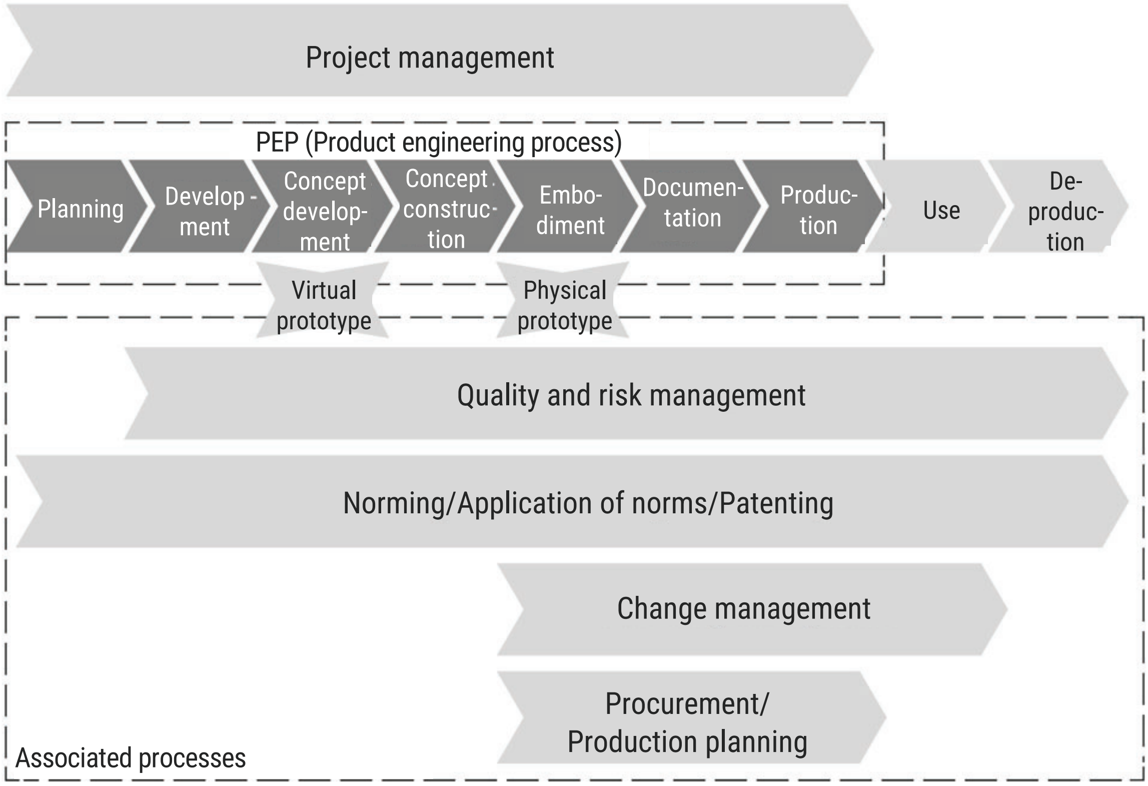


Figure 21: Product Engineering Process by (Feldhusen & Grote, 2013a, p. 23).

(Feldhusen & Grote, 2013a) also consider the development of products with multiple generations, variants and product families, but it is not their main focus. A detailed description of processes is also given. However, no consideration of smart products and smart factories is done. In addition, only the product development process up to manufacturing is considered, not the use and the end-of-life phases.

3.3.3.7 Product Lifecycle by Niemann & Pisla

Niemann and Pisla describe in their work published in 2021 that a product lifecycle consists of three phases the "design phase", "usage phase", and the "end-of-life phase". The design phase describes activities from conception to production and installation. The usage phase includes the products' operation and maintenance, and the end-of-life phase includes product updates, recycling and disposal (Niemann & Pisla, 2021, p. 11).

In the design phase, Niemann and Pisla use the general four-phase problem-solving circle approach and the procedure model according to VDI 2221. The four phases include the analysis of the problem and situation (I); the formulation of the problem and goal (II); the synthesis of the systems (III); and the evaluation and decision of the solution (IV). The four phases are transferred to the procedure model of VDI 2221 and are shown in the following Figure 22.

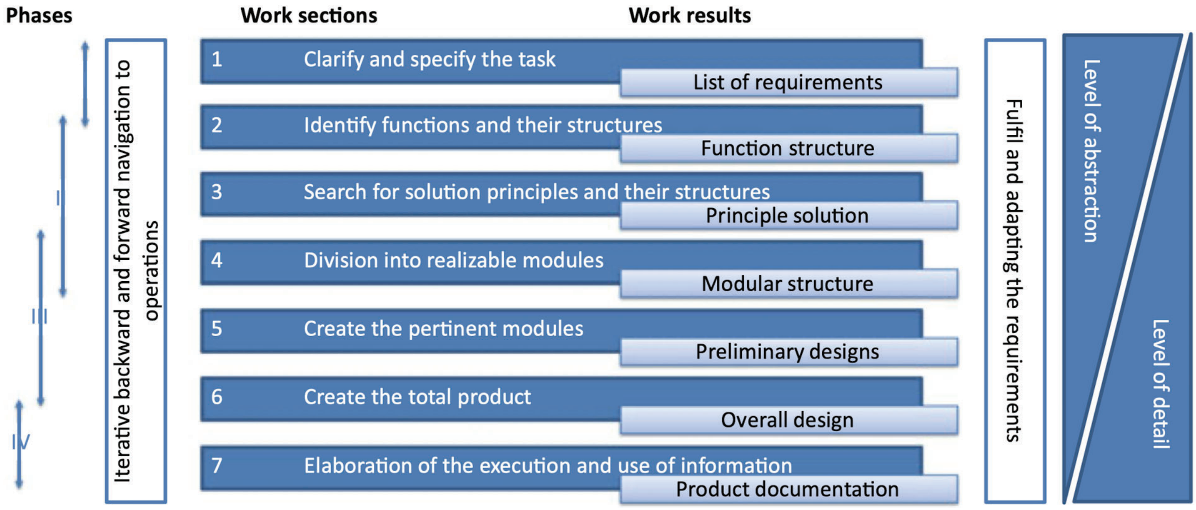


Figure 22: Design phase model (Herrmann, 2010; Niemann & Pisla, 2021, p. 18; VDI, 1993).

From the company's point of view, the main component in the use phase is maintenance. This consists of service, curative maintenance, corrective maintenance and improving the maintainability of the product.

The end-of-life phase consists of recycling and disposal. Four strategies are proposed for this, which are shown in the following Figure 23. In the direct reuse strategy, products are returned directly to the use phase and reused for the same application for which they were originally intended. In the remanufacturing strategy, used products are refurbished through manufacturing processes (e.g., repair or cleaning). In the recycling strategy, products are broken down into their raw materials in order to be reused in a new lifecycle. The worst end of the lifecycle from an environmental point of view is the end as waste. This is where products or their components end up if they cannot be directly reused, remanufactured or recycled (Niemann & Pisla, 2021, pp. 37-42).

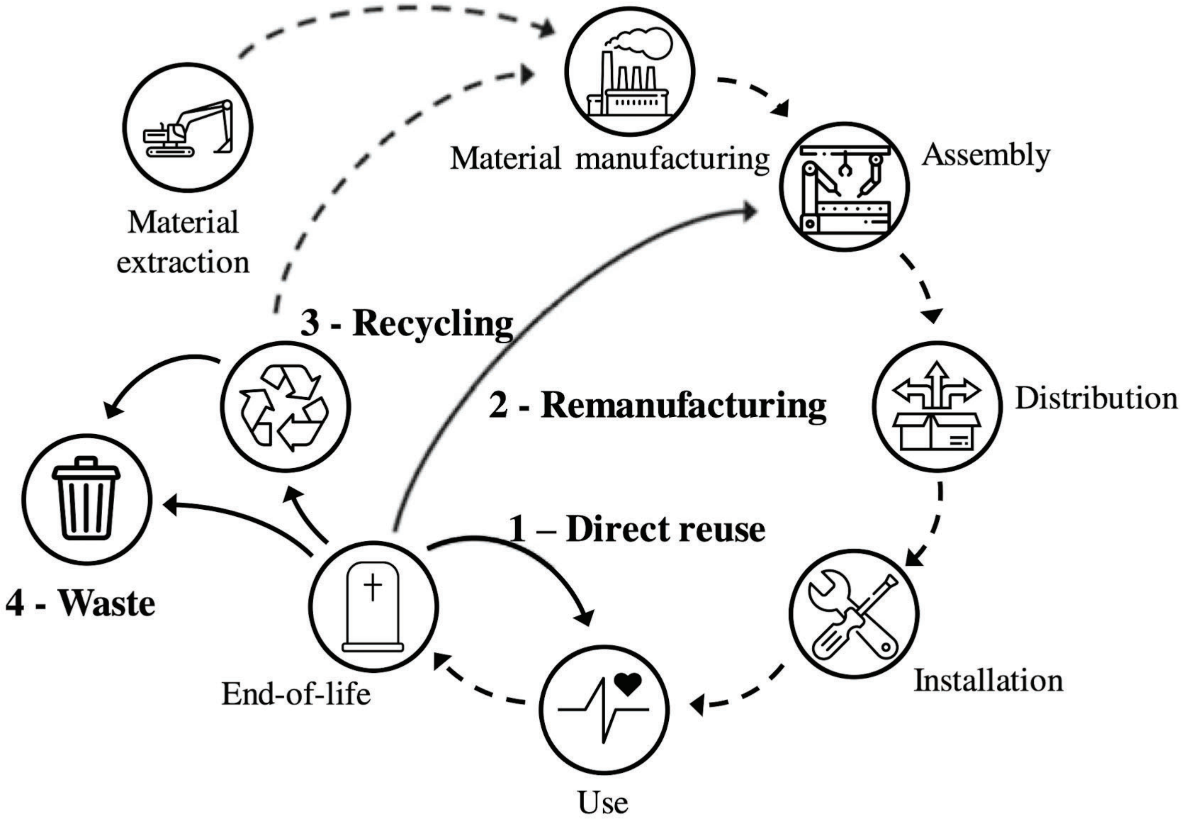


Figure 23: The four end-of-life strategies in circular economy (Niemann & Pisla, 2021, p. 37).

Furthermore, Niemann and Pisla present a framework that shows which phases of the lifecycle process information provided by the design phase and which phases provide information as feedback for the design phase of new products (Niemann & Pisla, 2021, pp. 57-58). This framework is shown in the following Figure 24.

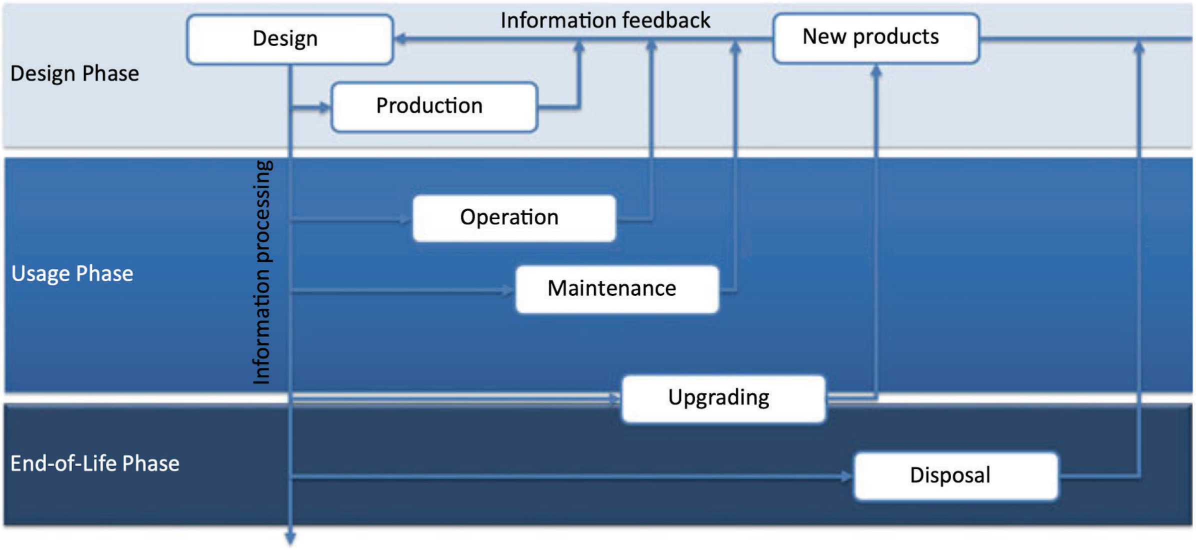


Figure 24: Information flows in a product lifecycle (Niemann & Pisla, 2021, p. 58).

The product lifecycle by Niemann and Pisla considers the complete product lifecycle from idea to end-of-life. It also gives a toolbox of methods for the phases of the product lifecycle. It can be used for the development of smart, modular, customisable product families, even if this is not the focus of the model.

However, it only provides rough steps for the different lifecycle phases and does not describe the activities in detail. It also does not consider the development of smart products and their integration into the smart factory in particular. Thus, it puts production in the centre.

3.3.3.8 Engineering in Product Lifecycle by Jiang

According to (Jiang, 2015, p. 11), the product lifecycle is divided into the main phases pre-manufacturing, manufacturing, and post-manufacturing.

The pre-manufacturing phase can be divided into two parts. It starts with the front-end stage, where the need is identified, and the project plan and the product's requirements are defined. The product is designed and developed in the design and development process stage. The stage ends with the testing and optimisation of prototypes of the product.

In the main manufacturing stage, the production system (including supply chain design, production planning, system layout and tool selection) is designed, the production system is operated, and the quality of the production system is monitored.

The post-manufacturing phase is divided into marketing, post-sale support (spare parts support, installation service) and retirement (recycling, refurbishing and remanufacturing) (Jiang, 2015, pp. 11-24).

Jiang describes a model in which the entire product lifecycle is described with a focus on manufacturing. Information on the main phases and individual activities is given, but not in detail. Furthermore, it is not apparent whether the model has been tested in practice. It is suitable for modular product families but does not provide explicit guidance on the development of modules, platforms, and their architecture. Through the descriptions of data types, it forms a basis for the development of smart products and productions.

3.3.3.9 Virtual product development based on systems engineering and RFLP

Systems engineering is used to solve complex problems at the system level (Stark et al., 2012, pp. 1-4). In the mechatronic field, systems engineering is divided into three main phases. These are system analysis, system development and system integration. In this model, the V-model, according to Systems Engineering, was combined with the RFLP approach for the development of mechatronic products. RFLP stands for requirements engineering (R), functional design (F), logical design (L) and physical design (P) (Kleiner & Kramer, 2013, pp. 93-98).

In the system analysis, requirements (R) are defined, functions (F) are analysed, the logical architecture (L) is developed, specifications are described, and the physical design (P) of the product is formed. In the system development phase, product development data, e.g. CAD models, are created. In the system integration phase, the components are validated, tested, and integrated into the overall system, where they are further validated and verified (Kleiner & Kramer, 2013, pp. 93-98). This model is illustrated in the following Figure 25.

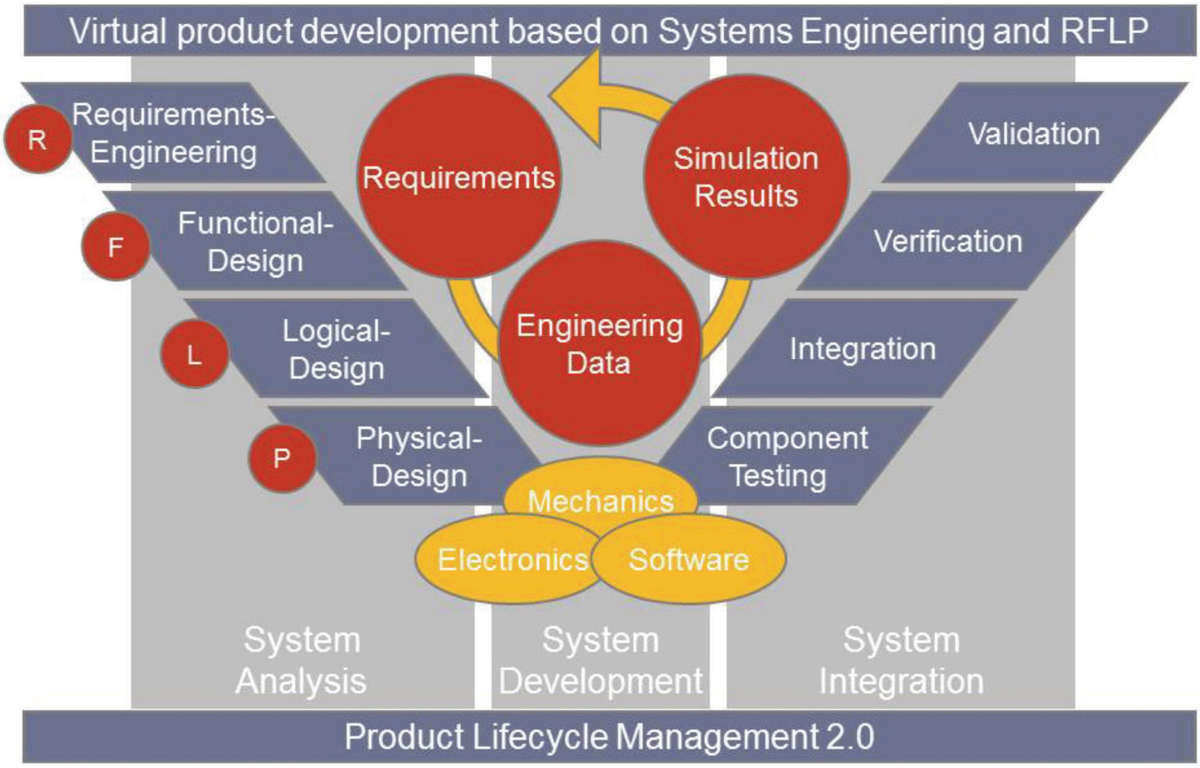


Figure 25: Virtual product development based on systems engineering and RFLP (Kleiner & Kramer, 2013, p. 95).

The development model is suitable for the development of customisable modular product families. It is also suitable for the development of smart products. However, the model stops after the validation of the products and therefore does not span the entire product lifecycle.

3.4 Generative design

Because humans can only remember a certain number of variables, they are inferior to machines in various tasks. Since a large number of variables can exist in a design process and a constructor is limited by his imagination and experience, computer-assisted support lends itself. This can go far beyond the computer only calculating constructions until it determines the construction itself. Especially in mass customisation, an automatically developed design could speed up the design process.

3.4.1 Definition of generative design

Generative design is a design process, which generates novel, but efficient and buildable designs based on defined requirements with computer support (Krish, 2011, p. 90). Basically, there are two main advantages of generative design. On the one hand, shapes are proposed that a designer could not have imagined and that new complex forms are possible in combination with additive manufacturing. On the other hand, time can be saved through automation.

In contrast to conventional design, in which the designer considers the shape of the product on the basis of the given requirements, the first step in generative design is to describe the requirements for the component. For instance, the installation space, forces, dimensions, moments and material can exist as requirements. Based on this, the algorithm calculates possible buildable constructions without human interaction that meet the requirements and provides a solution space of multiple constructions from which the designer can select the most suitable solution according to shape, weight, material consumption and many other factors (Autodesk, 2022; Krish, 2011). According to (Trautmann, 2021, p. 94), generative design enables the customer to become a designer. He can choose the most suitable solution without having deep knowledge of design technology.

3.4.2 Application of generative design in product lifecycles

In general, generative design is used in the product design and production phase of mechatronic products. It can be used in various industries such as automotive, architecture or clothing (Trautmann, 2021, pp. 87-94).

Generative design is predominantly located in product development but also partly in production planning. (Li & Lachmayer, 2018, pp. 1-3) developed an approach that uses generative design to generate design alternatives in order to support the designer later in the creation of designs. Due to the fact that the design procedure has not been widely described in the literature, a framework has been developed by (Li & Lachmayer, 2018, p. 2), which is shown in Figure 26.

The approach begins by defining the design requirements for the product. Then the product is divided into individual design zones, and the design is structured in this way. Once the product characteristics and functions have been defined, a design skeleton is developed. Based on this skeleton, the modelling structure, connecting elements, and the assembly structure are developed. Based on the configuration and parametrisation, a variety of solutions can be proposed using generative design, and a solution can be selected using design knowledge (e.g., about the design process and production properties). The design model is iteratively validated and further improved until an appropriate solution emerges (Li & Lachmayer, 2018, pp. 1-3).

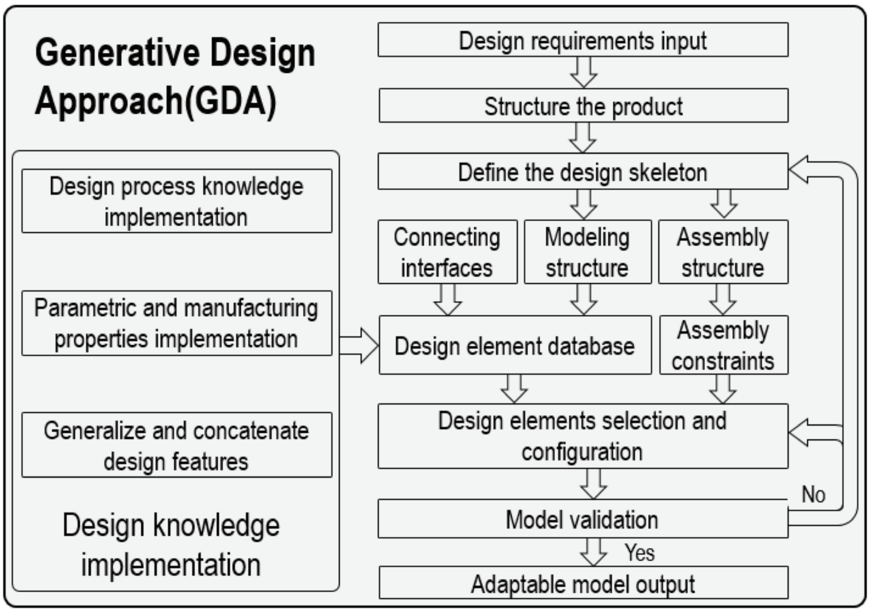


Figure 26: Generative Design Approach (Li & Lachmayer, 2018, p. 2).

3.5 Cause-and-effect relationships

Cause-and-effect relationships represent interrelationships in the object of investigation. In the context of this work, cause-and-effect relationships are used to identify the relationships in a product lifecycle and, as a result, to develop a new type of product lifecycle.

3.5.1 Definition of cause-and-effect relationships

In a cause-and-effect relationship, there is a relationship between one variable and one or more others. The relationship is characterised by the fact that a change in one variable causes a change in the other variable. A cause-and-effect relationship is said to exist when the change in the variables occurs at the same time, or one event immediately precedes the other, or when it is unlikely that variable two will change even though variable one has not changed. In order to identify a cause-and-effect relationship, it must be ensured that there is a connection between the cause and effect and that they are not just closely linked (Kent, 2006).

One process that builds on cause-and-effect relationships is quality problem-solving (QPS), which is used in the manufacturing industry. This process consists of problem definition, problem analysis, cause identification, solution generation and selection, and solution implementation and testing (MacDuffie, 1997, p. 481). The data that exists in a QPS system includes the problem, the causes, different types of solutions and a solution evaluation. If the problems and causes are represented graphically, the result is a bipartite graph (Xu & Dang, 2020, p. 5359).

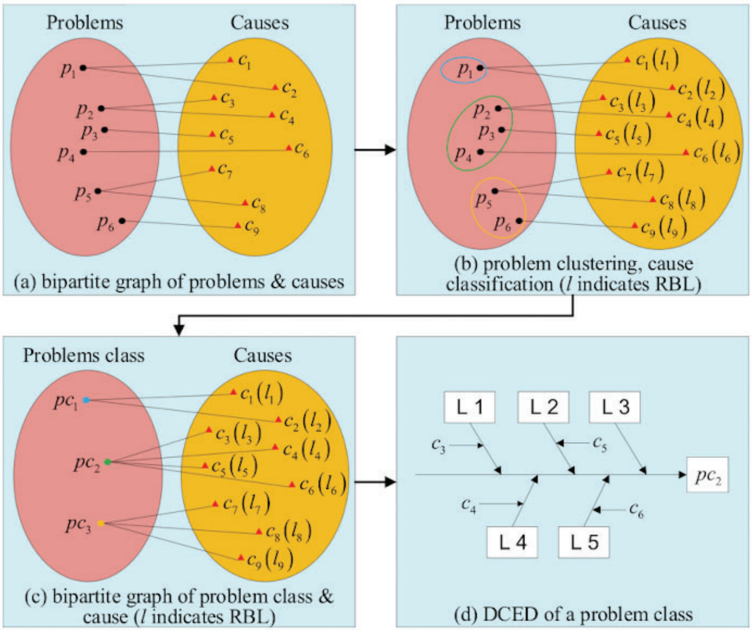
The cause-and-effect diagram (CED) is a qualitative analysis tool used for QPS to graphically show and analyse the relationship and causality between problems and causes. The CED (also known as Ishikawa or fishbone diagram) method was first introduced by a Japanese Manager called Ishikawa. A distinction is made between the abstract cause-and-effect diagram (ACED) and the detailed cause-and-effect diagram (DCED) (Xu & Dang, 2020, pp. 5360-5362).

3.5.2 Development procedure of cause-and-effect relationships

In the first step, all problems and causes are identified in a bipartite relationship. This mostly happens with the help of brainstorming and personal experience. Then the problems (problem groups) and causes (main cause cluster or rib branch label) are both clustered as a preparation for the CED. Subsequently, the bipartite relationship between problem class and cause class is determined based on the predefined relationships and clustering (Xu & Dang, 2020, p. 5360).

When creating a CED, the first step is to create the main cause categories for the problems, also called rib branches. Then, with the help of brainstorming and personal experience, all possible causes are identified. The next step is to classify the causes and sort them into classification categories. This clarifies the affiliation between the causes and main categories. The final step is to analyse the causes, select them and evaluate how they affect the problem. Subsequently, the two-way relationship between problem class (pc) and cause class (cc) is determined based on the predefined correlations and clustering. In the Ishikawa, the respective problem class is then represented as the head and the respective rib branch labels with its causes as the bones. The DCED differs from the ACED in that in the DCED only the problems are clustered (Xu & Dang, 2020, p. 5360). The generation of a DCED is shown in the Figure 27.

In the context of this work, cause and effect relationships can be applied to identify interrelationships in a product lifecycle. This involves investigating which problems can exist in a product, what the possible causes are and what solutions to these problems might look like. After identifying the interrelationships, processes can be derived from them to see through which areas information flows to implement solutions, as well as how problems can be eliminated or avoided automatically.



(a) bipartite graph of problems & causes

(b) problem clustering, cause classification (*l* indicates RBL)

(c) bipartite graph of problem class & cause (*l* indicates RBL)

(d) DCED of a problem class

Figure 27: Generation of a DCED (Xu & Dang, 2020, pp. 5360-5364).

3.6 Conclusion

New technologies and developments by companies offer a variety of potentials for the product lifecycle. In order to provide a theoretical basis about the environment and current trends, Industry 4.0, smart factories and smart customisable product families are described in this chapter. Industry 4.0 technologies and smart factories provide a basis for collecting data about production and the overall company. The trends and the development of standards create the possibility to use data for business processes. One of the elements of Industry 4.0, which is expected to have a high potential, is mass customisation. Smart customisable product families play an important role in mass customisation, and interrelationships become more complicated due to the interfaces in and between individualised products and the product family. To exploit the possibilities of smart products and smart factories, it requires an advanced data management system that can handle the heterogeneous data and make it usable for all phases of the product lifecycle. However, to improve product properties and the efficiency and effectiveness of processes around the product families, it is imperative to use the data and information from the entire lifecycle (Huang et al., 2007, pp. 292-306; Pan et al., 2014, pp. 869-870).

On the topic of the product lifecycle, theoretical foundations about product lifecycles and current product lifecycles and product engineering processes were described and evaluated. As there is only little process automation in the process models presented, generative design was introduced as a technology for automating product and process development.

The cause-and-effect relationships serve as the basis for describing a methodology for the creation of the new model. Cause-and-effect relationships and their procedure were presented. Cause-and-effect relationships can be used to analyse complex relationships in a system. These relationships can be used to identify areas where processes are relevant.

Chapter 4 Identification of cause-and-effect relationships and relevant data types

The overall objective of this chapter is to form a basis for creating processes that solve problems that exist in conventional product lifecycles.

4.1 Procedure for determining cause-and-effect relationships and solution approaches

The procedure for identifying problems and their causes and transforming them to Ishikawas is shown in the following Figure 28.

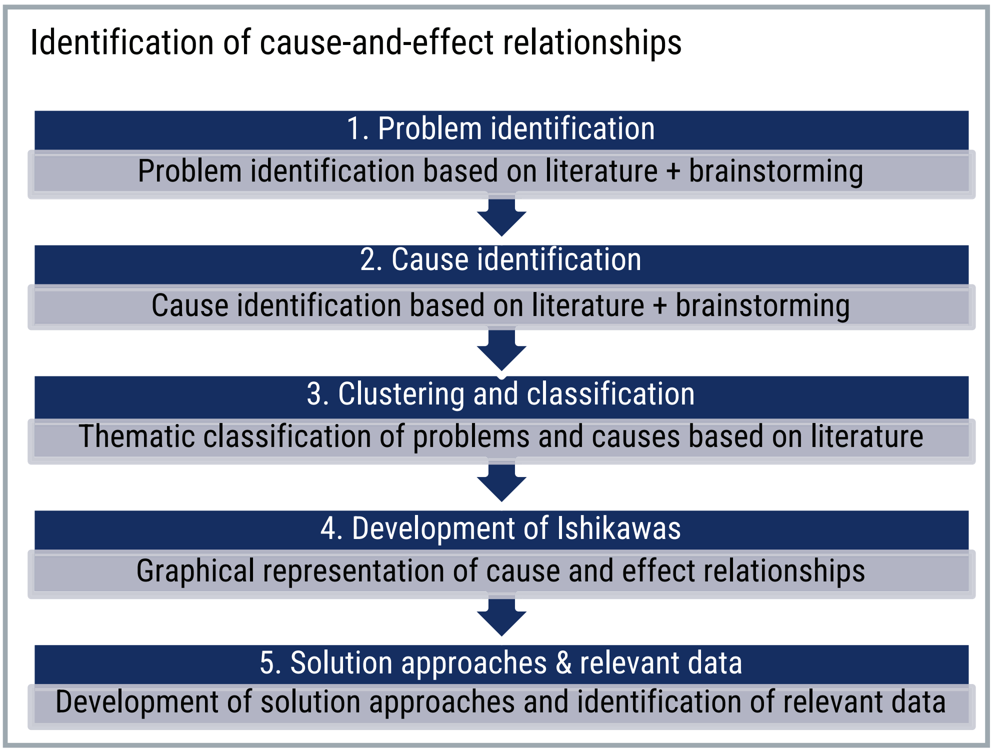


Figure 28: Procedure for determining solution approaches and relevant data on the basis of CERs based on (Xu & Dang, 2020, pp. 5360-5364).

The procedure is based on the CED creation process of (Xu & Dang, 2020, pp. 5360-5364) and is extended by the creation of solution approaches and the identification of relevant data. In the first step of the procedure, the problems and causes are identified and classified using literature. This is also enriched by personal experience through brainstorming. From this, Ishikawas are generated, and solution approaches and relevant data are developed.

In the context of this work, the identification of cause-and-effect relationships is focused on the technical area of a company.

4.2 Cause-and-effect relationships in a product lifecycle

Cause-and-effect relationships from pre-development, product and process development, resource engineering, use phase and end-of-life phase are identified and listed in the following.

4.2.1 Cause-and-effect relationships in pre-development

While there is still a high degree of uncertainty, primary framework conditions for the product are defined in pre-development. These framework conditions include product characteristics, material, assembly concepts and production concepts (Kohlbeck et al., 2020; Kohlbeck et al., 2021, p. 119). The cause-and-effect relationships are shown in Figure 29.

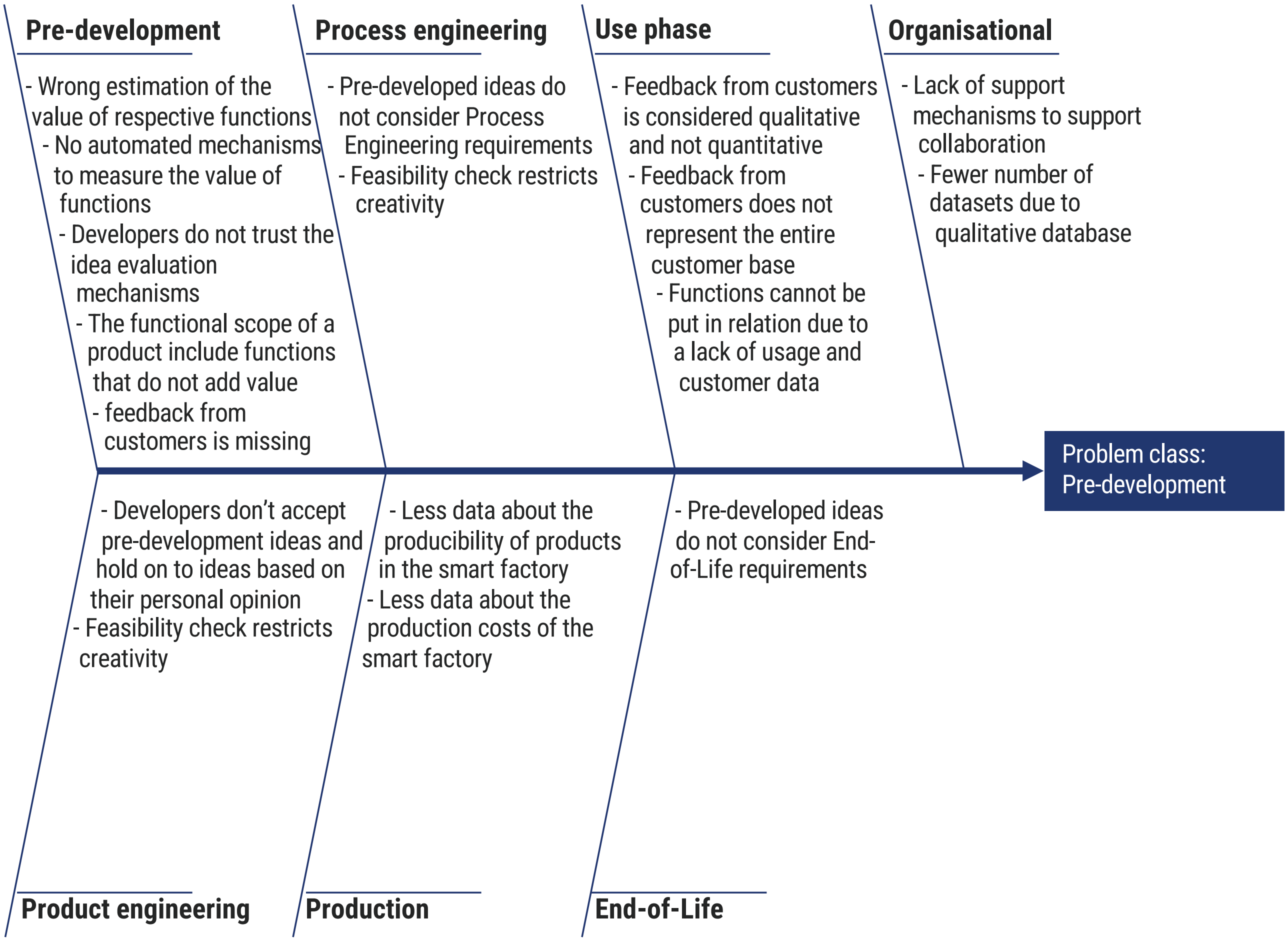


Figure 29: Cause-and-effect-diagram for problem class "pre-development".

According to (Moeckel & Forcellini, 2007, p. 477), portfolio management is often subjective, and there is less repeatability in the results of pre-development. These are problems in the process of pre-development. This subjectiveness in pre-development comes from a lack of support mechanisms to support collaboration and knowledge transfer in this phase. Subjectivity is also partly shaped by limiting considerations about feasibility testing of the product engineering and process engineering phase. As the causes fall into the processes of knowledge management and project management, these can be ascribed to the rib branch label (RBL) organisational processes. One solution to this is to invest in the technological infrastructure to turn intangible aspects into tangible ones and to work collaboratively on decision-making (Moeckel & Forcellini, 2007, p. 477).

In most companies, the pre-development phase is the phase in which it is decided whether a product idea should be developed further or not. The decision is based on the expected estimated value (which is made up of several factors). One problem is that companies often do not know how much respective functions are worth and thus continue to pursue the wrong product ideas. This is because mostly the database for the estimation of the value is fed by qualitative data, which keeps the number of data sets low. This creates a high risk of error in the evaluation of the idea. This risk exists because there is a lack of mechanisms to measure customer value in the assessment of production capability. The reason for companies not knowing the value of functions of the product is that they do not have mechanisms to measure the customer value of functions (Johansson et al., 2015, pp. 58-59).

Furthermore, there are no mechanisms that consider previous generations' experience in production to include producibility and production costs in the value of the idea. Data collection mechanisms are needed to determine the value of features in a product. Smart product technologies enable one to collect and analyse data directly from the product. Furthermore, the data of a smart production, which consists of a Digital Twin and historical data, provides a basis for evaluating the ideas from a production perspective. This makes it possible to demonstrate customer benefits and quantify functions (Johansson et al., 2015, p. 59).

Often, developers hold on to ideas based on their personal opinion because they do not trust the evaluation mechanism. In addition, feedback from customers is usually missing in pre-development. Customers are involved in a preliminary study in small numbers, if at all. This means that feedback from customers must be considered qualitative and not quantitative. This usually involves asking only one group of customers, resulting in qualitative information about the idea but not representing the entire customer base. In order to represent the entire customer base, quantitative data on customer feedback should exist. The data recording of the smart products can be used for this purpose, whereby conclusions can be drawn about user behaviour. For instance, sensor data from a chassis can be used to initiate new products in pre-development, as a need can be identified. On the other hand, this user data can also be used as a product requirement. For instance, temperature data from an insulation box can be used to define the wall thickness of a product in advance (Johansson et al., 2015, pp. 58-59).

Another problem is that the functional scope of the product is usually defined in pre-development, which means that functions are included that do not add value. This also leads to the development of functions that many users do not need. Often, the broadest possible range of functions is integrated into the product to cover all possible user needs since the individual functions cannot be put in relation to each other. If detailed user data were available from previous generations on the use of functions, this could be included in the selection of the range of functions (Johansson et al., 2015, p. 61).

4.2.2 Cause-and-effect relationships in product engineering

The trend shows that more and more products are to be launched on the market. The survival and profitability of companies now depend on the number and quality of newly developed products. It is also proven that a fast introduction to the market results in a longer product lifecycle due to the higher market share that is gainable if the product is launched before that of the competition (Lieberman & Montgomery, 1988, pp. 41-58). This requires a fast development of products, and for this, all slow processes have to be accelerated (Ali Yassine & Sally Souweid, 2021, p. 1). The resulting and further problems, as well as their causes, are shown in Figure 30.

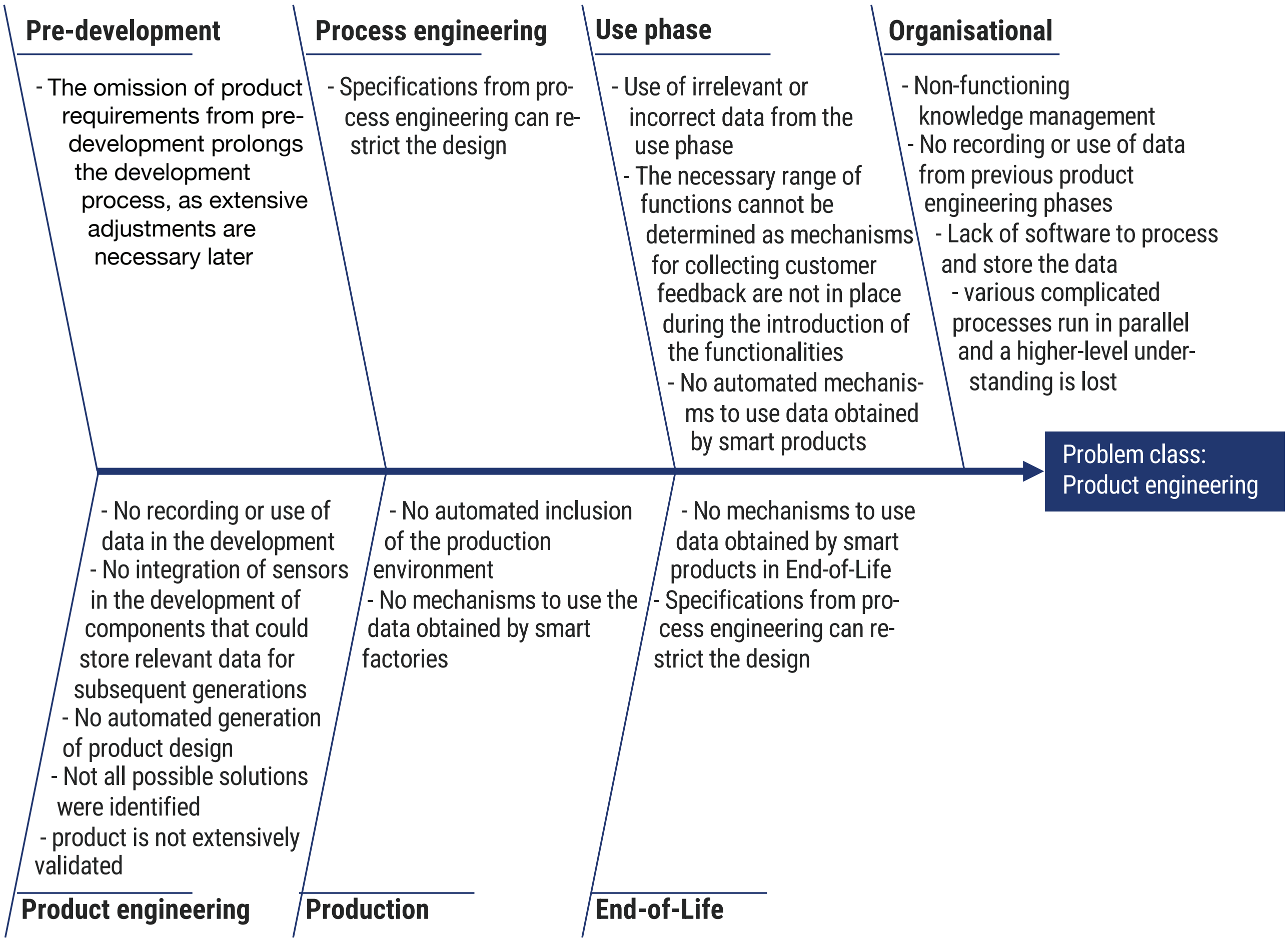


Figure 30: Cause-and-effect-diagram for problem class "product engineering".

Problems that stand in the way of the rapid development of products are lengthy processes for their introduction. These can be caused by the lack of automated integration of the production environment, which can lead to profound changes in production (e.g., new tools, new mountings), being required for new products, or the lack of automated integration of requirements for the product. These can be attributed both to customer requirements and based on experiences from previous use phases. One solution could be the integration of a uniform platform in which all requirements for both the production and the use phase can be assigned to the product. Another solution can be a functioning knowledge management system, which provides the knowledge from the future phases in the product lifecycle for product development. However, a prerequisite for knowledge management is that data is also recorded for this purpose. This data should be as relevant as possible and collected from all phases of the product lifecycle. In particular, problems can arise with the transfer of information from the use and prototype phase to the engineering phase. For this purpose, it must be planned in advance where sensors are additionally necessary and useful for data collection.

Another problem that arises with the acceleration of development processes is that traditional design processes are too time-consuming. In the conventional design process, time is consumed by the manual creation of designs. Generative design can provide a remedy through the automated creation of designs (Autodesk, 2022). Deriving from this, however, a comprehensive requirements list is needed from the knowledge management system, which sets out the requirements for production, use and disposal. Moreover, a problem that accompanies with a rapid market launch is that the quality and performance of products suffer as a result. By working through issues as quickly as possible, details are left out, and the product is not extensively validated. This can lead to problems and product recalls during use (Querbes & Frenken, 2017; Suarez & Lanzolla, 2005; A. Yassine & S. Souweid, 2021, p. 1). One approach to solve this problem is, on the one hand, to let the details flow into the product requirements automatically via a platform and, on the other hand, to validate the product on the basis of user data in precisely the same way as it is used.

Nevertheless, for product engineering there are restrictions from process engineering. For example, specifications from process engineering can restrict the design. The solution is a close exchange in which an overlapping of the requirements is sought.

A general problem is that there is no feedback of data collected from smart products and smart factories from other phases of the product lifecycle in product engineering. This is also accompanied by the problem that the user experience is not incorporated into the product design. There is no return flow of data from smart factories and smart products from the production phase and no return flow of data from the smart product from the use and end-of-life phase. The reason for this in each case is that there are no mechanisms for analysing and using the data obtained by the smart product or smart production. This could be remedied by developing and integrating mechanisms in product development for analysing and using the data (Roto et al., 2018; Tomiyama et al., 2019, pp. 12-13).

During the development of products, the problem can arise that decisions are made on the wrong knowledge basis. This is usually the case when various complicated processes run in parallel; knowledge is not managed, and a higher-level understanding of the development processes is lost. To prevent this, processes in development must be structured so that knowledge can be developed, distributed and used in a company (Ahmed et al., 2020, p. 246). Instead of making wrong decisions about possible solutions, the problem can also be that the best solution has not been identified at all. This is usually since not all possible solutions can be worked out and evaluated because of the limited time available. This problem can be solved through a combination of precise product requirements and process automation.

In the development of products, functions are often developed in many improvement loops to such an extent that they are ready for all applications and situations. Sometimes the customer does not need the full scope and is already satisfied with a part that provides the most significant added value. All further product improvements that cover even more situations and use cases offer no added value. However, it is difficult for companies to assess whether the necessary range of functions has already been achieved, as mechanisms for collecting customer feedback are not in place during the introduction of the functionalities (Bosch-Sijtsema & Bosch, 2015; Johansson et al., 2015, p. 61). One solution would be to collect and analyse data on user behaviour during the introduction and use phases of the functionalities.

4.2.3 Cause-and-effect relationships in process engineering

In order to bring a product to market as fast as possible, the time required for process engineering must also be reduced, so that little time is lost in preparing for production. Several factors (e.g., tooling time, productivity, tooling outlay) can increase the number of working days in the process engineering phase (Hillnhagen et al., 2021, pp. 889-890). These factors and other causes are shown in Figure 31.

On the one hand, the process of implementing a new product can be lengthy if the production environment is not considered in the product development, and thus the product or production must be changed extensively. On the other hand, during the implementation of the production site, the product is often changed. This happens when the producibility of the product is not checked in advance. Even if the production environment was considered manually in the product development, errors could occur due to the manual process (A. Yassine & S. Souweid, 2021, pp. 1-16). Therefore, an automated process for considering the production environment during development is recommended.

This should contain not only the dimensions and tools but also quality data from which design recommendations can be derived. The solution approach would also reduce the risk of new tools being needed for new variants. Additionally, it reduces the risk that adaptation measures are necessary in production when a new variant is introduced, which at the same time can also reduce the number of production prototypes. This is because completely new designs are often created rather than building on previous products. Conversion measures and a high number of production trials also result in costs, which are based on the fact that synergies with other variants were not used. In addition, pre-development can lead to the problem that production technologies are selected that are not yet in use or have not been tested. Also, historically established paradigms lead to the whole solution space not being considered (Jagusch et al., 2019, 2020; Jericho et al., 2020, pp. 890-891).

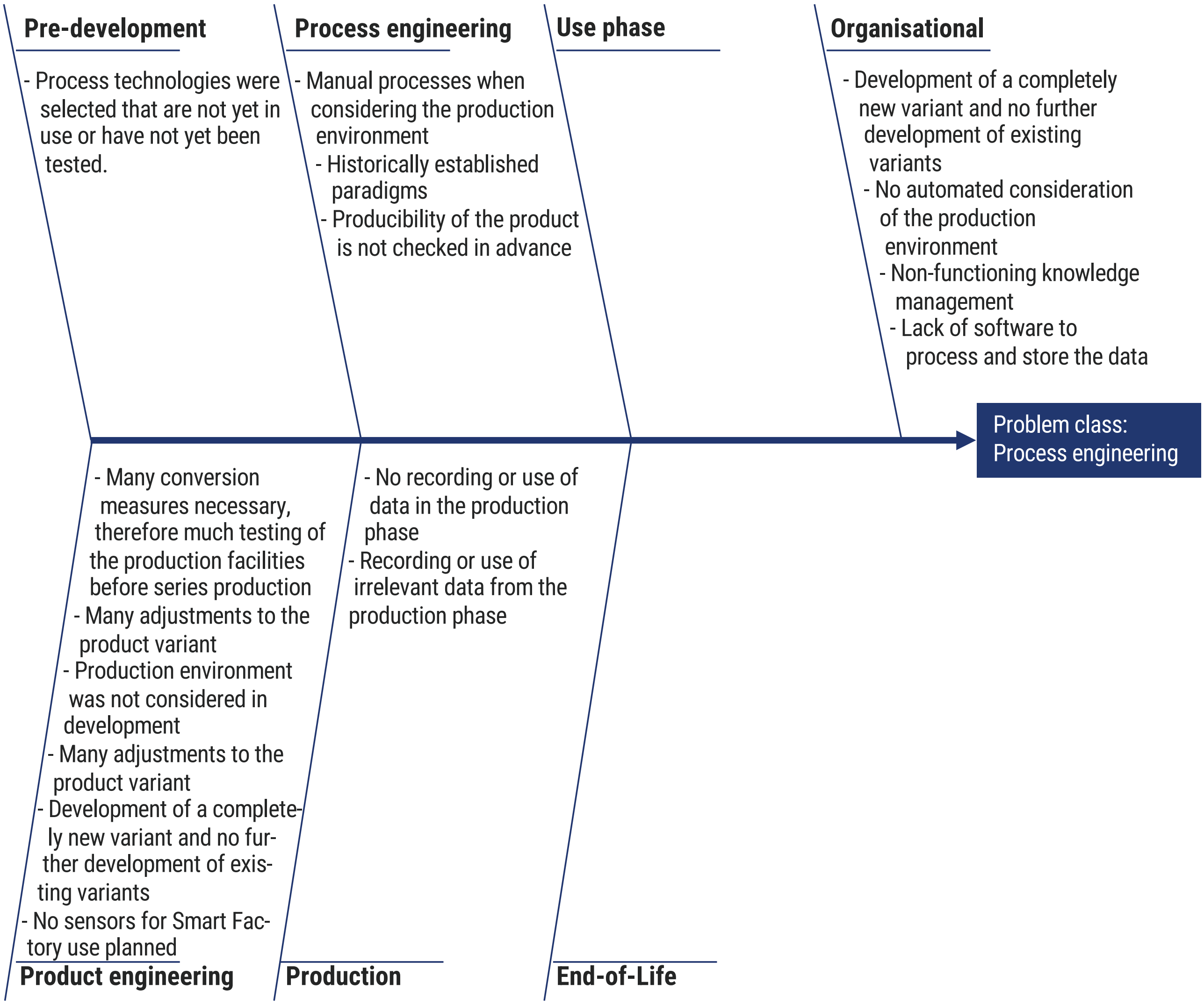


Figure 31: Cause-and-effect-diagram for problem class "process engineering".

Basically, knowledge management is also an elementary component in process engineering because it requires information from nearly every lifecycle phase (Gernhardt et al., 2018, p. 181). The problem could be that knowledge about the production of previous products is not passed on. The causes for this are a non-functioning knowledge management system, where data in the production of other variants are either not included or not used for subsequent generations. Another reason for this can be a lack of software for processing the data or that no sensors are installed in the various components. One approach to solve this problem would be to provide a comprehensive knowledge management system in the form of a database that can process the data from production and make it available to process engineering (Gernhardt et al., 2018, p. 199).

4.2.4 Cause-and-effect relationships in production

The production phase is an important problem class in a product lifecycle, as this is where the product becomes real. Within this phase, problems arise that are primarily internal in origin and whose causes usually lie in the previous phases of the product lifecycle. In addition, it offers many opportunities for problem elimination, as it is the last internal phase before the utilisation phase and data exists from both the smart product and the smart factory for analysis and evaluation. The cause-and-effect relationships are shown in Figure 32.

In mass customisation, an innumerable number of variants are produced in the production process. This poses a significant challenge to the people in production, as almost every product is new to them. The problem is that the quality of a product can suffer due to a large number of variants (Beckschulte et al., 2021, p. 189). As a result, it can happen that a product or its component is defective, and this defect is not detected. The reason for this is that employees must perform different work steps for each variant.

On the one hand, the employee can be overburdened with the assembly or handling of the different variants and, on the other hand, with the quality control of variants (Liu et al., 2020, p. 554). One approach to solve this problem is to reduce the complexity of the variants by developing product families with uniform interfaces (Beckschulte et al., 2021, p. 189). Also, in production itself, the employee can be supported by trainings, display panels or augmented reality. This can be realised, for example, by displaying instructions for the work steps during assembly and quality control close to the employee's working area. These additional instructions for the worker must be planned during the process engineering phase.

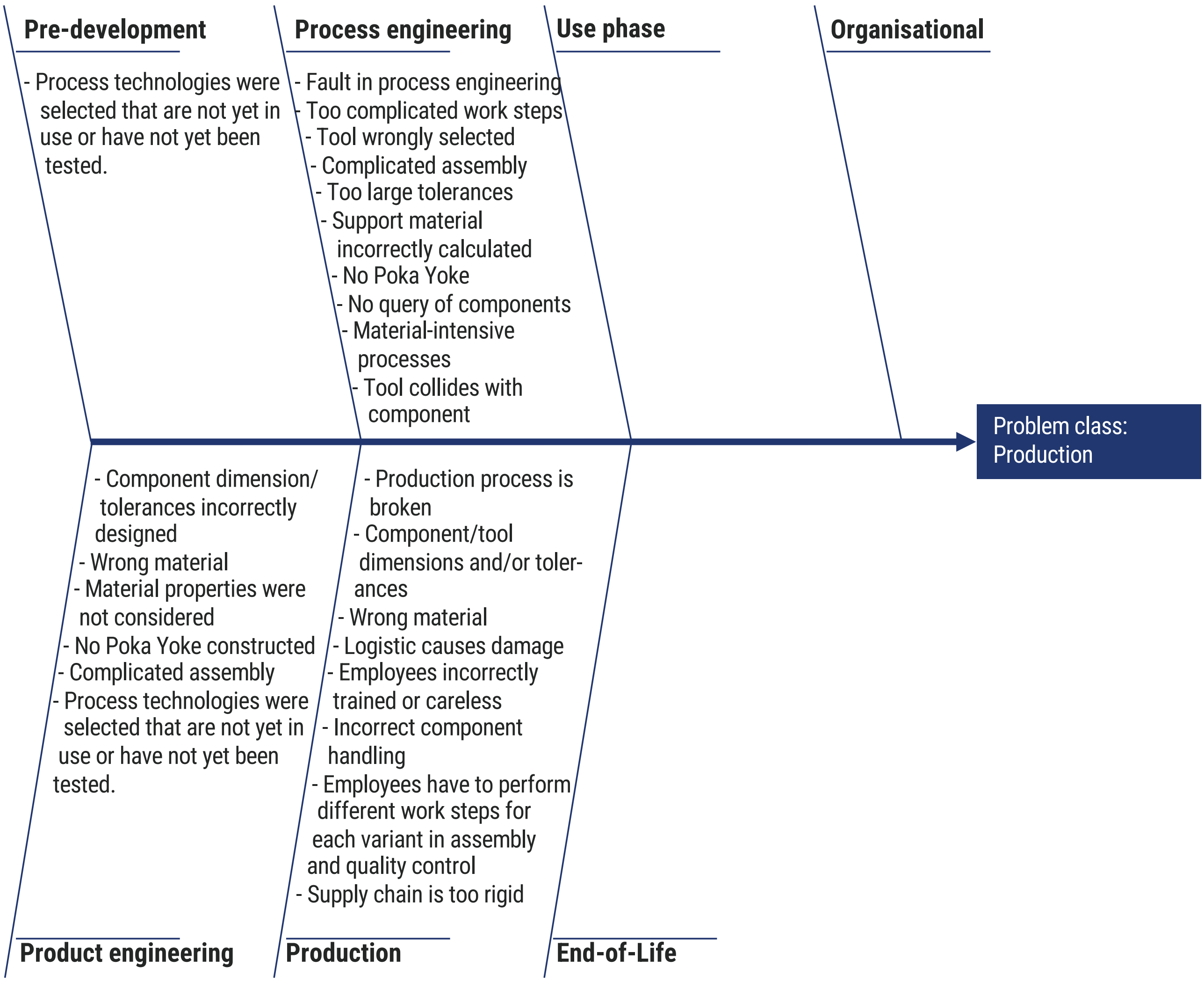


Figure 32: Cause-and-effect-diagram for problem class "production".

Quality data from previous generations or variants can be used to evaluate where there is a need for support for the employee. The correct installation and presence of customisable components could also be checked by sensors, which must be planned in the process engineering phase. To avoid costly sensors, Poka-yoke, which is a methodology to avoid faults through specific construction guidelines (Klanitz, 2022), could also be planned in the product engineering phase in the design of the components or in the process engineering phase. In addition, a product defect or that a product dysfunctionality occurs when a production process is disrupted, or if there is a defect. Disruptions can occur, for example, if manufacturing technologies that have not yet been tested are selected in pre-development or product and process engineering. Maintenance plans of the relevant machine should be reviewed if machine defects occur frequently. A product defect can also occur when the tolerances of a component have been calculated incorrectly, resulting in damage to the product in the production process (Wittmann & Stockinger, 2006, p. 159). Damage to the product or that components cannot be connected together can also result from incorrectly selected material. However, product defects can also result from faulty process engineering. For example, support technologies for reducing the complexity of manual work with many variants may not have been planned in during process engineering, or tools and their tolerances may have been incorrectly designed so that they collide with the components. In general, a suitable shop floor management system can be recommended within the production phase, which controls and improves production by recognising deviations and problems (Rauch et al., 2018, pp. 17-21).

Among the new production technologies offered by Industry 4.0 is additive manufacturing. This enables the printing of topology-optimised shapes. Moreover, it is used in most cases of mass customisation. However, process-dependent limitations can lead to problems between development and production. For example, in the context of a lunchbox, a component may not be produced correctly or may break during production if too little wall thickness was used, if the support material was calculated incorrectly, or if the available 3D printing material does not meet the requirements. These parameters can also be machine-type dependent, which means that consideration of the parameters of the available machines should be planned for in the development in order to be able to manufacture the product in the desired quality. A complicated design that requires a lot of support material, for example, can also increase the cycle time of 3D printing. In order to avoid the problems of 3D printing, the requirements of 3D printing should be known in the product engineering phase, and the design should be aligned accordingly (Lange, 2021, p. 2).

In addition, problems that arise in logistics can originate in the product lifecycle. A factor that can cause product defects is when the component is damaged in logistics, e.g., by inappropriate load carriers. Additionally, due to the increasingly complex supply chain, the problem often arises when delivery does not occur at the right time in the production phase. This is caused by a supply chain that is too rigid and too complex. As a derivation, a solution approach to make the supply chain flexible is the coupling of a reconfigurable supply chain with a reconfigurable product. The possibilities for reconfiguring the supply chain should already be taken into account when developing the possible variants (Lapusan et al., 2019, p. 377).

4.2.5 Cause-and-effect relationships in use phase

In the use phase, the product is delivered to the customers and used by them. Individual users differ in the type of use, number of uses, and satisfaction. Depending on the use, problems may arise with some or all of the users. Users are requiring ever higher demands on the quality and reliability of the product. This means that companies must be able to react to defects as quickly as possible (Günther et al., 2022, p. 187). Until now, the return flow of this use data has only been possible in a cumbersome way, even though this use data can provide enormous potential. The cause-and-effect relationships are shown in Figure 33.

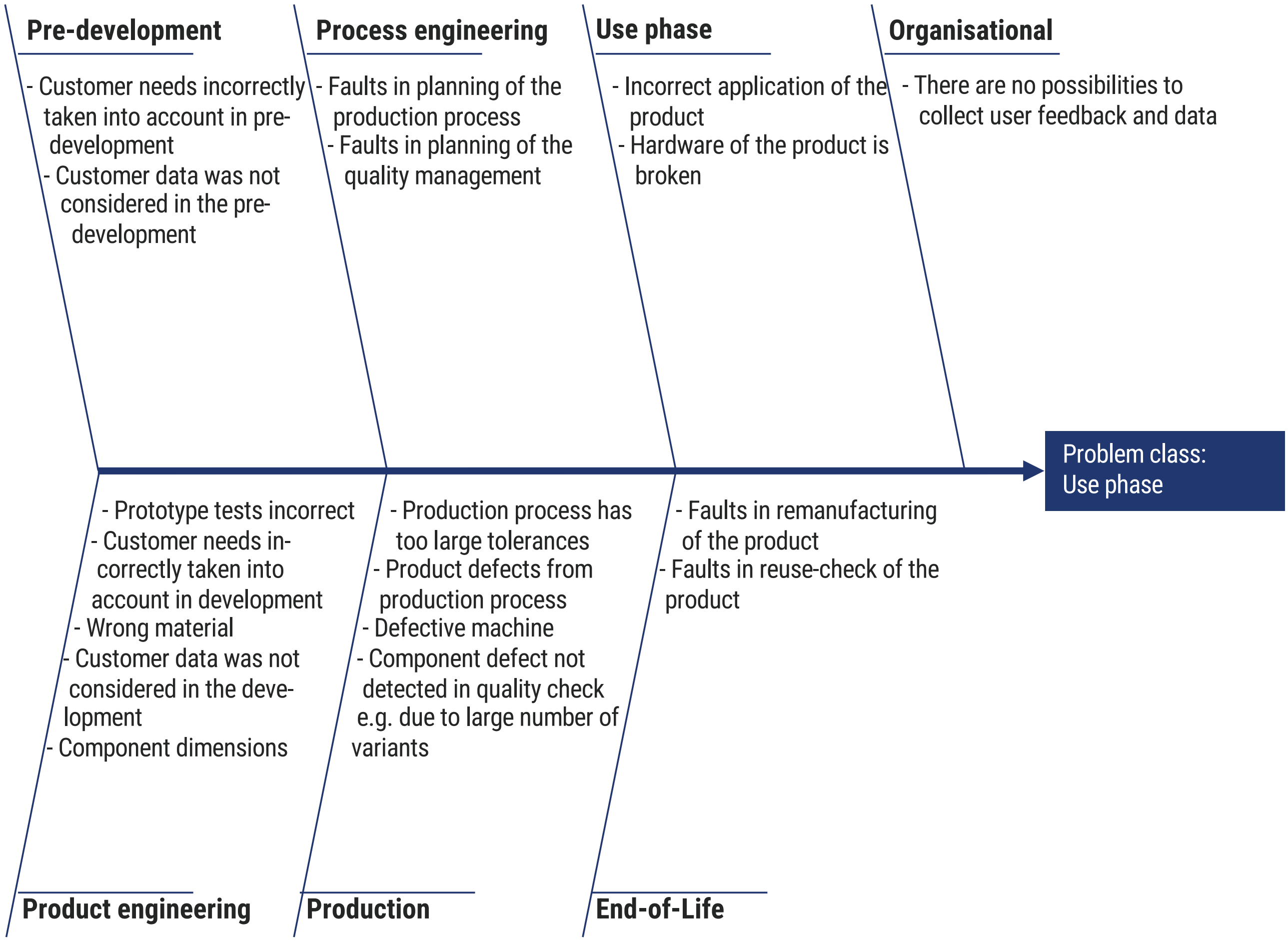


Figure 33: Cause-and-effect-diagram for problem class "use phase".

A problem that can occur during the use of products is that the product or its components do not fulfil the original function. As a result, the product cannot be used as intended by the customer. This can have many causes, which may lie in product engineering, process engineering, production, or in the use phase itself. Causes that can be traced back to a faulty pre-development or product engineering phase are that the wrong requirements were placed on the product (e.g., inappropriate material, faulty tolerances, faulty design), or that the actual customer needs were not defined as a requirement. Due to the missing requirements, prototype tests might also not have been carried out realistically. In order to achieve a better understanding of the customers in the product engineering phase, capabilities should be created to include customer information. This can be realised, for example, through extensive data-driven requirements engineering (Wei et al., 2022, p. 1). Problems can also originate from production due to a faulty production process. On the one hand, this can be because the production process is incorrectly designed due to faulty process engineering. Quality problems may arise in production as a result, or they may not be recognised. On the other hand, the problem can be caused directly from production, for example, if defective machines disrupt the production process. This problem can be solved by a functioning quality management system that identifies the possible sources of disturbances already existing in process engineering and schedules testing of possible component defects in quality management. This inspection plan should be iteratively adaptable through a process that learns from the user data (Günther et al., 2022, p. 187).

During the use phase itself, a product defect can occur if the user does not use the product properly or a component breaks. Proper product use can be improved through user-led development and instructions, and to avoid the defect in the future, information about defective components can be sent back to development.

Product defects can also occur when a product has been remanufactured or reused via an end-of-life strategy. During remanufacturing, a defect may occur when components are replaced, or defective components may not be detected, and during reuse, a defect may not be detected in quality control. Furthermore, the product may become defective much earlier, as it has already been used for a more extended period.

4.2.6 Cause-and-effect relationships in end-of-life

End-of-life concludes the product lifecycle. According to (Niemann & Pisla, 2021, p. 37), there are four strategies that a company can follow. The product can either be directly reused, remanufactured, the materials recycled, or thrown away. The cause-and-effect relationships for those four strategies are shown in Figure 34.

Generally, a product’s lifecycle ends with recycling or disposal when there is a defect in the product, or a component and the product can neither be reused nor remanufactured. If recycling is not possible, disposal of the product is the only option, and this should be avoided as much as possible with the core idea of the circular economy. If disposal is the only possibility, it makes the products themselves a problem. For this reason, end-of-life strategies should already be integrated at the pre-development phase.

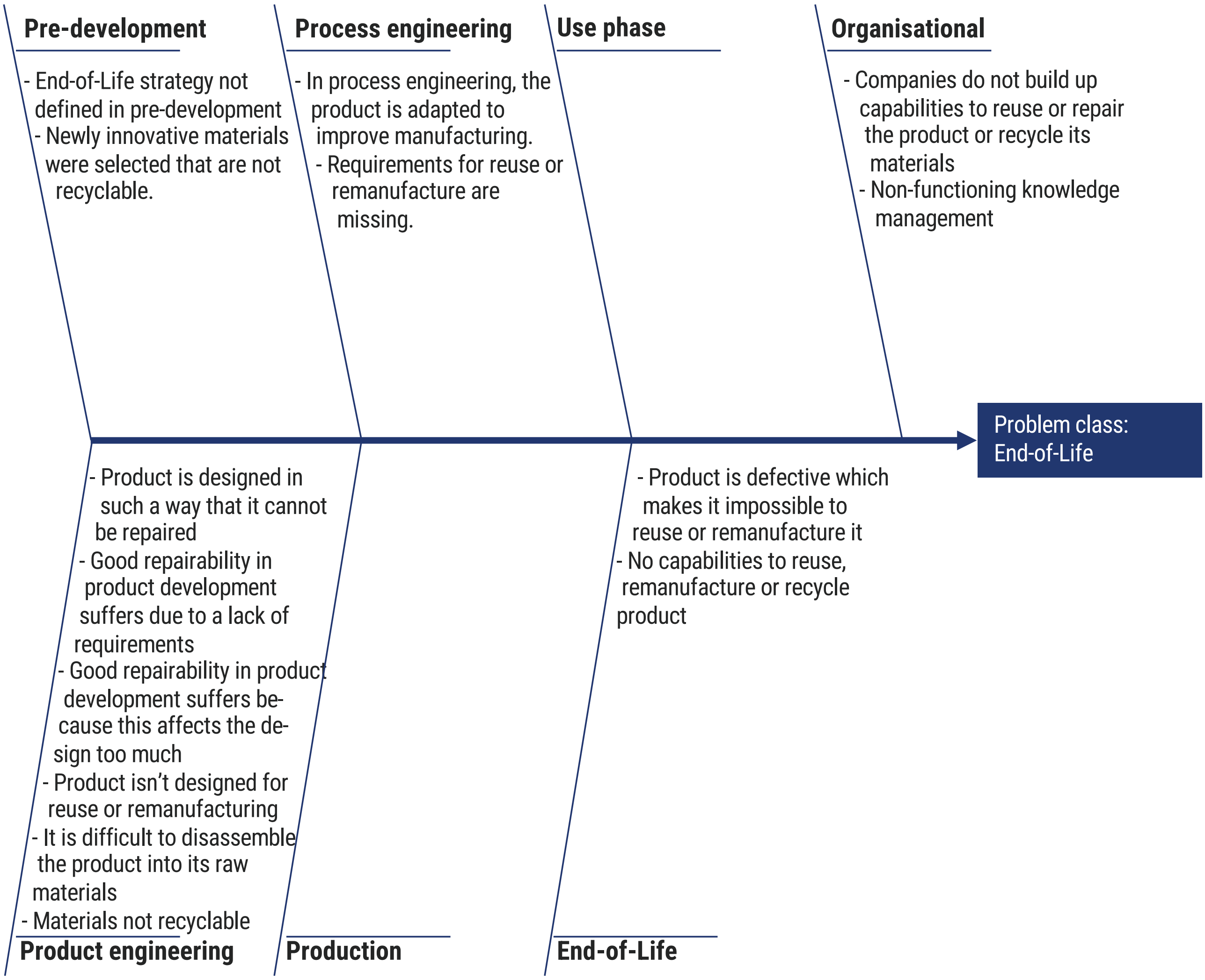


Figure 34: Cause-and-effect-diagram for problem class "end-of-life".

A component can only be directly reused if it still fulfils its functions. The reuse strategy cannot be applied if components or the entire product is no longer functioning. Then it is to be checked whether the product can be remanufactured. The problem can arise that the design or construction of the component prevents remanufacturing. This is the case when a product is designed in such a way that it cannot be repaired. The fact that a product is not repairable can also be done purposefully in some cases so that a customer does not repair the product cheaply but buys a new one. However, this has a significant, negative effect for the environment, and with such products, the profit is in the foreground. But there are also non-malicious intentions, so that good repairability in product engineering suffers due to a lack of requirements in pre-development or product engineering. Also, a good repairability could affect the design too much. Process engineering also has an influence on the design or assembly of products. In process engineering, the product is adapted to improve manufacturing. Requirements for reuse or remanufacture are missing. The reuse or remanufacturing could also be impossible if the product is defective. To ensure that the requirement for repairability at least exists in product and process engineering, requirements from the end-of-life phase should be brought back into the phases. The requirements can then lead to easily repairable designs, such as modular designs (Niemann & Pisla, 2021, pp. 57-58).

If the product cannot be reused or remanufactured, at least the materials of which the product is made can be recycled. The problem may be that the product is poorly recyclable. This may be because it is difficult to disassemble it into its raw materials or because the materials used in the product are poorly recyclable. Both are factors that could be taken into account in product engineering of the products. This can be implemented by setting requirements for product engineering from the recycling phase. These requirements can be newly established or based on historical data from previous products (Niemann & Pisla, 2021, pp. 57-58).

If the product cannot be recycled, the only choice is disposal. This alone represents a problem, the cause of which is that the product was not designed for a circular economy. In order to change this, many approaches and methods are available under the topic "circular economy" to develop the product in a reusable, recoverable or recyclable way. The fact that disposal of a product is the only option also occurs in companies that have not built up capabilities to reuse or repair the product or recycle its materials (Niemann & Pisla, 2021, pp. 57-58).

4.3 Relevant data types in product lifecycles

In order to be able to determine the relevant data in the product lifecycle, the procedure developed by (Günther et al., 2022, pp. 188-189) is used. This recommends using process analyses to identify the relevant influencing factors and sources of problems. The problems from the creation of the cause-and-effect relationships are used and build the basis for the creation of an overview of data streams in the product lifecycle. A selection of relevant data sources is given for each of the data streams. The resulting data sources are evaluated by means of criteria. The criteria include the relevance and reliability of the variables, availability, characteristics of the data streams and aspects of data security for the customer. It is also distinguished whether the data originates from previous generations or from the current one. In the follow-up step, additionally required data sources are determined based on requirements from systems (Günther et al., 2022, pp. 188-189).

4.3.1 Data streams in a product lifecycle of a smart customisable product family

The data streams were developed using the cause-and-effect relationships from the previous Section 4.2. This involved looking at what problems exist in which phases of the product lifecycle, the cause behind them and how these problems can be solved with the help of data from other phases. If data generated in the phase contributes to preventing or solving problems in other phases, this is labelled with an output of data. If data from other phases is needed to solve problems originating from this phase, this is labelled with an input of data.

The Figure 35 shows the data streams in a product lifecycle of a smart customisable product family. In the horizontal plane the figure shows the six main phases of a product lifecycle from pre-development to end-of-life. The blue boxes indicate each phase of the product lifecycle and give indications to the vertical input and output data streams. At each stage, data is generated that can be further used in the next generation in that stage as part of knowledge management. A distinction is made between the input and output data streams as to whether they originate from the current or previous generation.

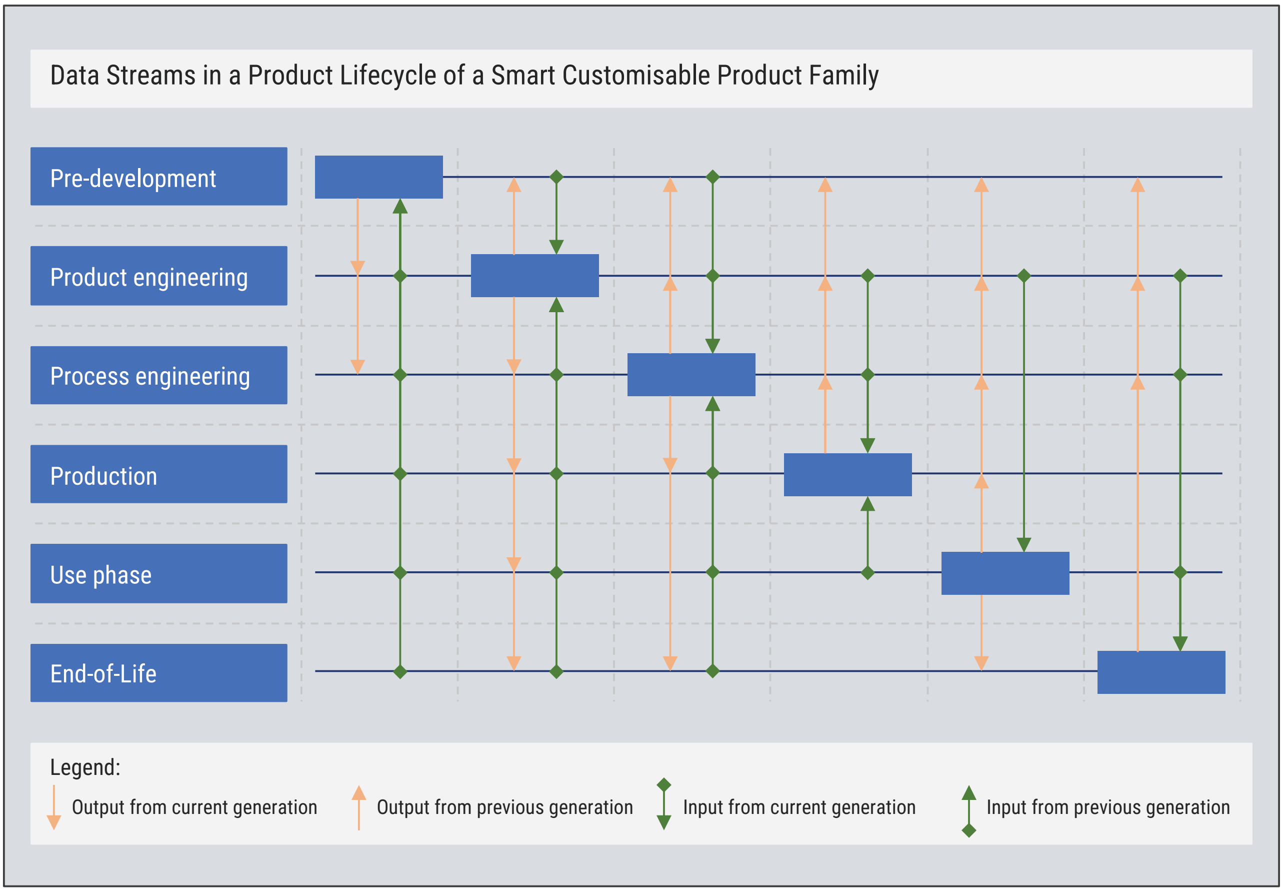


Figure 35: Data streams in a product lifecycle of a smart customisable product family.

A detailed overview and description of the data types, including their characteristics, is given in the following Sections 4.3.2 - 4.3.7.

4.3.2 Data types in pre-development

Within the pre-development phase, it can be seen that output data is only generated for product and process engineering. These include the concept and architecture, among other data about the product and production idea. Also, information is given about the corresponding stakeholders and use cases.

However, if the perspective is changed to what input data can be used to improve pre-development, the following can be derived: Data flows in from all other phases, because ideas for new products can arise in any phase

On the one hand, this can be seen as a feedback loop in which pre-developers see what influence their ideas have on the other product life phases (e.g., idea feasibility, test results), but also as a method for implementing potentials in the other product life phases (e.g., potentials in production, quality, use and end-of-life). Data from the use phase can also provide a basis for evaluating ideas more precisely. The different data types are shown in Table 5 (Allmann, 2007, p. 1).

Table 5: Relevant data types in pre-development.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
Pre-Development	Product Engineering	X		Product idea	Medium	Low	High	Low
Pre-Development	Product Engineering	X		Product concept	Medium	Medium	High	Low
Pre-Development	Product Engineering	X		Product architecture	Medium	Medium	Medium	Low
Pre-Development	Product Engineering	X		Stakeholder	Medium	Medium	Medium	High
Pre-Development	Product Engineering	X		Use cases	Medium	High	Medium	Low
Pre-Development	Process Engineering	X		Production concept	Low	Low	Low	Low
Pre-Development	Process Engineering	X		Production technologies	Low	Low	Low	Low
Pre-Development	Process Engineering	X		Production process	Low	Low	Low	Low
Product Engineering	Pre-Development		X	Idea feasibility	Medium	High	Low	Low
Product Engineering	Pre-Development		X	Prototype test results	Medium	High	Medium	Low
Product Engineering	Pre-Development		X	Scope of adaptation of the idea	Low	Medium	Low	Low
Process Engineering	Pre-Development		X	Feasibility of the idea in production	Medium	High	Low	Low
Process Engineering	Pre-Development		X	Data of the production process	High	High	High	Low
Process Engineering	Pre-Development		X	Predicted key performance indicators	High	High	High	Low
Production	Pre-Development		X	Key performance indicators	High	High	High	Low
Production	Pre-Development		X	Quality data	High	High	High	Low
Production	Pre-Development		X	Potentials in production	High	Medium	Medium	Low
Use Phase	Pre-Development		X	Key performance indicators	High	Medium	Medium	Medium
Use Phase	Pre-Development		X	Data about usage	High	Medium	Medium	High
Use Phase	Pre-Development		X	Quality data	High	Medium	Medium	Medium
End-of-Life	Pre-Development		X	Service life	Medium	High	Low	Low
End-of-Life	Pre-Development		X	Quality data (Reason for lifetime end)	High	High	Low	Medium
End-of-Life	Pre-Development		X	Data of reusing, remanufacturing and recycling	High	Low	Low	Low

4.3.3 Data types in product engineering

Since product engineering makes key decisions affecting all phases of the product lifecycle, input and output data streams flow into all phases of the product lifecycle. As a result, this phase forms a core for the exchange of data. Furthermore, it can also be observed that data can flow backwards from product engineering to pre-development as feedback that improves pre-development and thus forms an iterative process. As a basis for product engineering, it uses data from pre-development, which includes general information on the idea, architecture and use cases of the current generation, as well as data from all of the downstream phases of previous generations. This can be data about product performance in the production and use phase or about the product ability in the context of reusability, remanufacturing or recycling. In product engineering, data that provides essential product-related data for the process engineering, production, use phase, and end-of-life phases are generated. Also, data is generated as a basis for subsequent generations, e.g., to improve the interface between pre-development and product engineering. The data types are shown in Table 6.

Table 6: Relevant data types in product engineering.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
Pre-Development	Product Engineering	X		Product idea	Medium	Low	High	Low
Pre-Development	Product Engineering	X		Product concept	Medium	Medium	High	Low
Pre-Development	Product Engineering	X		Product architecture	Medium	Medium	Medium	Low
Pre-Development	Product Engineering	X		Stakeholder	Medium	Medium	Medium	High
Pre-Development	Product Engineering	X		Use cases	Medium	High	Medium	Low
Product Engineering	Pre-Development		X	Idea feasibility	Medium	High	Low	Low
Product Engineering	Pre-Development		X	Prototype test results	Medium	High	Medium	Low
Product Engineering	Pre-Development		X	Scope of adaptation of the idea	Low	Medium	Low	Low
Product Engineering	Process Engineering	X		Product properties	High	High	High	Low
Product Engineering	Process Engineering	X		Requirements for production processes	High	High	High	Low
Product Engineering	Process Engineering	X		Quality criteria	High	High	Medium	Low
Product Engineering	Production	X		Product properties	High	High	High	Low
Product Engineering	Production	X		Component handling	High	High	Medium	Low
Product Engineering	Production	X		Quality criteria	High	High	Medium	Low
Product Engineering	Use Phase	X		Instructions, manuals	Medium	High	High	Low
Product Engineering	End-of-Life	X		Instructions for remanufacturing	High	High	Low	Low
Product Engineering	End-of-Life	X		Instructions for recycling	High	High	Medium	Low
Product Engineering	End-of-Life	X		Quality criteria for reuse and remanufacturing	High	High	Low	Low
Process Engineering	Product Engineering		X	Feasibility in production	High	High	Medium	Low
Process Engineering	Product Engineering		X	Production properties	High	Medium	Medium	Low
Process Engineering	Product Engineering		X	Production process properties	High	Medium	Medium	Low
Production	Product Engineering		X	Key performance indicators	High	High	High	Low
Production	Product Engineering		X	Quality data	High	High	High	Low
Production	Product Engineering		X	Potentials in production	High	Medium	Medium	Low
Use Phase	Product Engineering		X	Key performance indicators	High	Medium	Medium	Medium
Use Phase	Product Engineering		X	Data about usage	High	Medium	Medium	High
Use Phase	Product Engineering		X	Quality data	High	Medium	Medium	Medium
End-of-Life	Product Engineering		X	Service life	Medium	High	Low	Low
End-of-Life	Product Engineering		X	Quality data (Reason for lifetime end)	High	High	Low	Medium
End-of-Life	Product Engineering		X	Data of reusing, remanufacturing and recycling	High	Low	Low	Low

4.3.4 Data types in process engineering

In the process engineering phase, on the one hand, product data from the previous phases and, on the other hand, data from subsequent phases of previous generations are used. This can be, for example, data about the product properties, about factors influencing the production capability, about the production process and its quality data, about quality data from the use phase or about the remanufacturing process. In addition, it generates data that can improve previous generations' pre-development and product engineering and provides data for the production and remanufacturing of products. The data types are shown in Table 7.

Table 7: Relevant data types in process engineering.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
Pre-Development	Process Engineering	X		Production concept	Low	Low	Low	Low
Pre-Development	Process Engineering	X		Production technologies	Low	Low	Low	Low
Pre-Development	Process Engineering	X		Production process	Low	Low	Low	Low
Process Engineering	Pre-Development		X	Feasibility of the idea in production	Medium	High	Low	Low
Process Engineering	Pre-Development		X	Data of the production process	High	High	High	Low
Process Engineering	Pre-Development		X	Predicted key performance indicators	High	High	High	Low
Product Engineering	Process Engineering	X		Product properties	High	High	High	Low
Product Engineering	Process Engineering	X		Requirements for production processes	High	High	High	Low
Product Engineering	Process Engineering	X		Quality criteria	High	High	Medium	Low
Process Engineering	Product Engineering		X	Feasibility in production	High	High	Medium	Low
Process Engineering	Product Engineering		X	Production properties	High	Medium	Medium	Low
Process Engineering	Product Engineering		X	Production process properties	High	Medium	Medium	Low
Process Engineering	Production	X		Data about production process	High	High	High	Low
Process Engineering	Production	X		Data about assembly process	High	High	High	Low
Process Engineering	Production	X		Quality criteria	High	High	High	Low
Process Engineering	Production	X		Production volumes and shifts	High	High	High	Low
Process Engineering	End-of-Life	X		Data about remanufacturing process	Medium	Medium	Low	Low
Process Engineering	End-of-Life	X		Data about disassembly process	Medium	Medium	Low	Low
Process Engineering	End-of-Life	X		Quality criteria for reuse and remanufacturing	Medium	Medium	Low	Low
Production	Process Engineering		X	Key performance indicators	High	High	High	Low
Production	Process Engineering		X	Quality data	High	High	High	Low
Production	Process Engineering		X	Potentials in production	High	Medium	Medium	Low
Production	Process Engineering		X	Data about the properties of production	High	Medium	Low	Low
Use Phase	Process Engineering		X	Quality data	Low	Medium	Medium	Medium
End-of-Life	Process Engineering		X	Feedback on the remanufacturing process	Medium	Low	Low	Low

4.3.5 Data types in production

In the production phase, data from product and process engineering are required. This is because the product is developed in the product engineering phase, and the production system in process engineering phase. Also, quality data from the use phase can influence the production, e.g., if a production process should be changed due to product defects. In production, important data is generated to improve subsequent products in terms of their producibility and quality in pre-development and product and process engineering. The different data types are shown in Table 8.

Table 8: Relevant data types in production.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
Production	Pre-Development		X	Key performance indicators	High	High	High	Low
Production	Pre-Development		X	Quality data	High	High	High	Low
Production	Pre-Development		X	Potentials in production	High	Medium	Medium	Low
Product Engineering	Production	X		Product properties	High	High	High	Low
Product Engineering	Production	X		Component handling	High	High	Medium	Low
Product Engineering	Production	X		Quality criteria	High	High	Medium	Low
Production	Product Engineering		X	Key performance indicators	High	High	High	Low
Production	Product Engineering		X	Quality data	High	High	High	Low
Production	Product Engineering		X	Potentials in production	High	Medium	Medium	Low
Process Engineering	Production	X		Data about production process	High	High	High	Low
Process Engineering	Production	X		Data about assembly process	High	High	High	Low
Process Engineering	Production	X		Quality criteria	High	High	High	Low
Process Engineering	Production	X		Production volumes and shifts	High	High	High	Low
Production	Process Engineering		X	Key performance indicators	High	High	High	Low
Production	Process Engineering		X	Quality data	High	High	High	Low
Production	Process Engineering		X	Potentials in production	High	Medium	Medium	Low
Production	Process Engineering		X	Data about the properties of production	High	Medium	Low	Low
Use Phase	Production		X	Quality data	High	Medium	Medium	Medium

4.3.6 Data types in use phase

In the use phase, data is generated that represents feedback and use from the customer. This data helps in the (pre-)development of new generations and in improving product and production quality. Data is also generated that provides information on the reusability of products. This is the case especially when a product is remanufactured and quality data about the second use phase is generated. Also, in the use phase, data from product engineering is used for instructions and user manuals. The relevant data types are also shown in Table 9.

Table 9: Relevant data types in use phase.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
Use Phase	Pre-Development		X	Key performance indicators	High	Medium	Medium	Medium
Use Phase	Pre-Development		X	Data about usage	High	Medium	Medium	High
Use Phase	Pre-Development		X	Quality data	High	Medium	Medium	Medium
Product Engineering	Use Phase	X		Instructions, manuals	Medium	High	High	Low
Use Phase	Product Engineering		X	Key performance indicators	High	Medium	Medium	Medium
Use Phase	Product Engineering		X	Data about usage	High	Medium	Medium	High
Use Phase	Product Engineering		X	Quality data	High	Medium	Medium	Medium
Use Phase	Production		X	Quality data	High	Medium	Medium	Medium
Use Phase	Process Engineering		X	Quality data	Low	Medium	Medium	Medium
Use Phase	End-of-Life	X		Data about the condition of the product	High	Low	Low	Medium
Use Phase	End-of-Life	X		Quality data from reused or remanufactured products	Medium	Low	Low	Medium

4.3.7 Data types in end-of-life

In the end-of-life phase, data from product and process engineering provide information on how a product can be reused, remanufactured, or recycled. In addition and depending on the end-of-life strategy of the product, various data are generated on the reusability of the product. Whether a product performs well or poorly in the circular economy can be tracked back via data. A list of relevant data types is shown in Table 10.

Table 10: Relevant data types in end-of-life.

Lifecycle Phase		Generation		Data types	Evaluation			
Input	Output	Current	Previous	Name	Relevance	Reliability	Availability	Data security
End-of-Life	Pre-Development		X	Service life	Medium	High	Low	Low
End-of-Life	Pre-Development		X	Quality data (Reason for lifetime end)	High	High	Low	Medium
End-of-Life	Pre-Development		X	Data of reusing, remanufacturing and recycling	High	Low	Low	Low
Product Engineering	End-of-Life	X		Instructions for remanufacturing	High	High	Low	Low
Product Engineering	End-of-Life	X		Instructions for recycling	High	High	Medium	Low
Product Engineering	End-of-Life	X		Quality criteria for reuse and remanufacturing	High	High	Low	Low
End-of-Life	Product Engineering		X	Service life	Medium	High	Low	Low
End-of-Life	Product Engineering		X	Quality data (Reason for lifetime end)	High	High	Low	Medium
End-of-Life	Product Engineering		X	Data of reusing, remanufacturing and recycling	High	Low	Low	Low
Process Engineering	End-of-Life	X		Data about remanufacturing process	Medium	Medium	Low	Low
Process Engineering	End-of-Life	X		Data about disassembly process	Medium	Medium	Low	Low
Process Engineering	End-of-Life	X		Quality criteria for reuse and remanufacturing	Medium	Medium	Low	Low
Use Phase	End-of-Life	X		Data about the condition of the product	High	Low	Low	Medium
Use Phase	End-of-Life	X		Quality data from reused or remanufactured products	Medium	Low	Low	Medium
End-of-Life	Process Engineering		X	Feedback on the remanufacturing process	Medium	Low	Low	Low

4.4 Conclusion

In summary, in the first step of this chapter the cause-and-effect relationships in the product lifecycle of a smart customisable product family in the context of multi-generational product development are described. Problem classes are identified for each phase of the product lifecycle, and their causes, and proposed solutions are identified. Based on this, a data stream diagram was constructed, which shows the data streams within the product lifecycle of current product types and, depending on the direction of the data stream, a classification into data processes for the current, previous, or next generation is made. These data streams now serve as the basis for creating the product lifecycle in the next step.

Chapter 5 Creation of the new comprehensive product lifecycle i^{2}PLM

This Chapter 5 forms the core of the thesis and presents the i^{2}PLM and its development. The procedure is illustrated in Figure 36. In the first step, a reference process is developed based on the product lifecycles and product engineering processes presented in the theory Chapter 3.3.3. In this manner, three product lifecycles most suitable for the product characteristics are converted into a uniform process diagram.

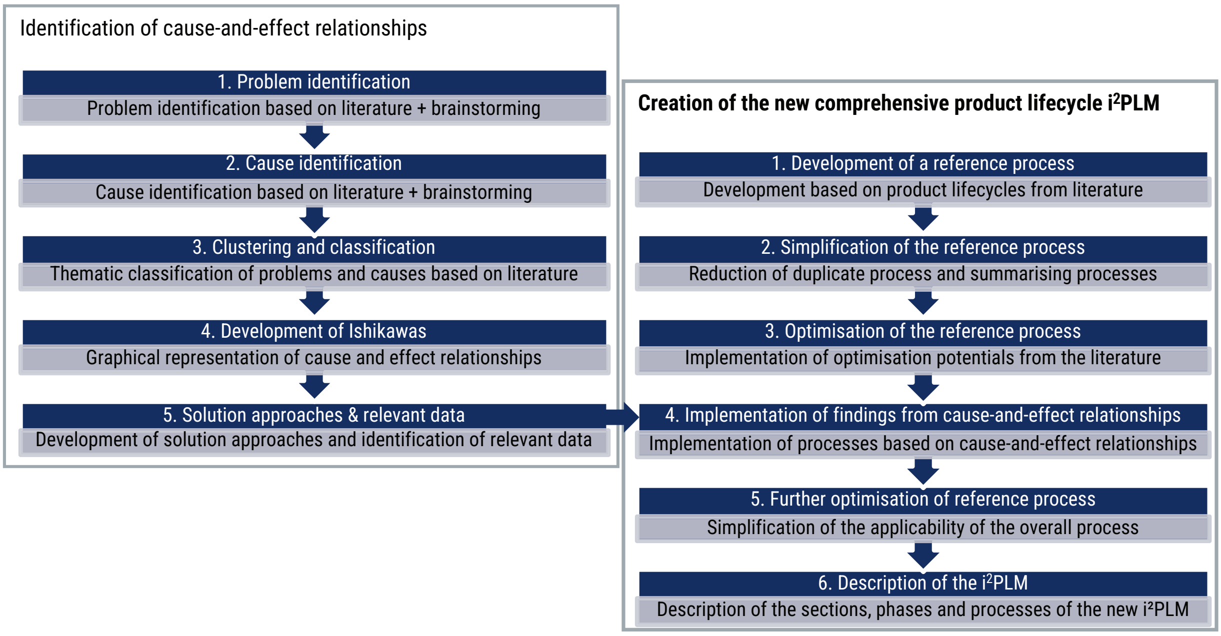


Figure 36: Procedure for the creation of the new product lifecycle i^{2}PLM based on (Xu & Dang, 2020, p. 5364).

In the next step, the three product lifecycles are combined into a single reference process that serves as a basis for further adjustments and optimisations. In the following step, general optimisation suggestions from the literature are implemented. In the next step, the transfer from Chapter 4 takes place, whereby the Ishikawa's and solution approaches are converted into processes of the i^{2}PLM. In this step, the relevant data streams are also included in the overall process diagram. Then the i^{2}PLM is further simplified by mainly optimisations. At the end of this chapter, the structure and processes, in general, are explained in general, and the implementation of a database solution using an i^{2}PLM tool is described.

5.1 Development and simplification of the reference process

In order to determine a reference process that can serve as the basis for the i²PLM, the first step is to select at least one from the multitude of product lifecycles in the literature that best meets the existing requirements. In the process, the requirements from Section 3.3.2 "Requirements for the reference process," are used as evaluation criteria when assessing product lifecycles. The evaluation is shown in Table 11.

Table 11: Evaluation table for comparison of product lifecycles.

Comparison Product Lifecycles			**Development of modular product structures**	**Products with multiple generations**	**Development of a product family**	**Development of smart products**	**Process engineering for a smart factory**
Name of PLC	**Authors**	**Published**					
VDI 2221: Methodology for developing and designing technical systems and products	VDI Verein Deutscher Ingenieure e.V.	2019	No	No	No	No	No
Integrated Product Engineering Model (iPEM)	Albers, Albert; Reiss, Nicolas; Bursac, Nikola; Richter, Thilo	2016	Yes	Yes	Yes	Yes	Yes
VDI 2206: V-Model	VDI Verein Deutscher Ingenieure e.V.	2004	Yes	No	Yes	Yes	No
Model of Architecting Steps	Otto, Kevin; Hölttä-Otto, Katja; Simpson, Timothy; Krause, Dieter; Ripperda, Sebastian; Moon, Seung	2016	Yes	Yes	Yes	No	No
Process for Production Planning	ProSTEP iViP e.V., Darmstadt	2010	No	No	No	No	Yes
Product Engineering Process	Feldhusen, Jörg; Grote, Karl-Heinrich	2013	Yes	Yes	Yes	No	No
Product Life Cycle	Niemann, Jörg; Pisla, Adrian	2021	Yes	Yes	Yes	No	No
Engineering in Product Life Cycle	Jiang, Renyan	2015	Yes	No	Yes	Yes	Yes
Virtual product development based on Systems Engineering and RFLP	Kleiner, Sven; Kramer, Christoph	2013	Yes	No	Yes	Yes	No

Among the processes presented in the literature, only the integrated product engineering model (iPeM) meets the requirements. It offers methods for developing products and product families with a modular product structure and several generations. The model can also be used to develop smart products and processes for manufacturing in a smart factory.

However, crucial disadvantages of the model are identified. First, it is strongly focused on the development of products and does not take much into account of the phases from the use phase till end-of-life. For this reason, the iPeM is extended to include phases of the product lifecycle by Niemann and Pisla. This is to balance the focus of the phases of the product lifecycle. In addition, the Niemann and Pisla model is suitable because it includes a proposal for information processing and feedback within the product lifecycle and for new products.

Sources:
[1] Feldhusen, J., & Grote, K.-H. (2013). *Pahl/Beitz Konstruktionslehre,* pp 21-23. Springer.
[2] Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP, 50,* 100-105. https://doi.org/10.1016/j.procir.2016.04.168
[3] Niemann, J., & Pisla, A. (2021). *Life-Cycle Management of Machines and Mechanisms,* pp.17-47. Springer.

Figure 37: Reference processes for the comprehensive product lifecycle based on (Albers et al., 2016, p. 5; Feldhusen & Grote, 2013a, pp. 22-23; Niemann & Pisla, 2021, p. 58).

Another disadvantage of iPeM is that the phases of product development are only roughly indicated, and it does not describe when the phases start and end. This is because the iPeM rather specifies which activities are necessary and covers less as how they are scheduled. Furthermore, no assignment to superordinate main phases is given. Therefore, the Product Engineering Process by Feldhusen & Grote is used as an additional supplement as it has a focus from pre-development to production. In Figure 37, the phases of the three reference processes are classified into the identified main phases. In order to be able to use the three reference processes for a reference process, they have to be merged. In the first step, duplicates and contradictions are removed. Then the processes are arranged in a waterfall diagram. The simplified reference process is shown in Figure 38.

Sources:
[1] Feldhusen, J., & Grote, K.-H. (2013). *Pahl/Beitz Konstruktionslehre,* pp 21-23. Springer.
[2] Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP, 50,* 100-105. https://doi.org/10.1016/j.procir.2016.04.168
[3] Niemann, J., & Pisla, A. (2021). *Life-Cycle Management of Machines and Mechanisms,* pp.17-47. Springer.

Figure 38: Simplified reference process for the comprehensive product lifecycle based on (Albers et al., 2016, p. 5; Feldhusen & Grote, 2013a, pp. 22-23; Niemann & Pisla, 2021, p. 58).

To simplify matters, the first step is to combine the three reference processes into one process image. iPeM is used as the primary process. In addition, the superordinate phases of the product lifecycle, according to Niemann and Pisla, are used for the iPeM, as these provide a uniform overview of the entire product lifecycle. The product engineering process developed by Feldhusen and Grote is inserted in the phases from pre-development to production. The phases "Documentation" and "Production" were removed, as these are already used in the other two models ("Knowledge Management" & "Production"). Since the information flows are fundamentally rebuilt on the basis of the cause-and-effect relationships and relevant data, the proposed information flows of the product lifecycle, according to Niemann & Pisla, are also removed in this step. In addition, the processes were graphically adapted for clarity.

5.2 Optimisation of the reference process

After all reference processes were inserted into a process diagram and combined into a reference process at the beginning, the fundamental adjustments to the model can now be made in the third step. For this purpose, three main adaptations were identified based on the literature analysis. These main adaptations include:

1. The development of processes with which data is recorded in the various phases of the product lifecycle for the current and/or subsequent generation.
2. The development of processes to analyse and process data in the different phases of the product lifecycle from the current and/or previous generation.
3. Connecting the development phases from production through iterative product and process engineering processes with feedback from production.

In the case of the main adaptations (1) and (2), the product lifecycle is shaped predominantly based on the cause-and-effect relationships and their resulting data streams. A uniform product lifecycle database is introduced to record, store and process a large amount of data. This database has the task of classifying enormous amounts of data in a uniform way, and drawing conclusions and analyses for current or future product generations. Thereby, it is essential to make the analyses accessible in a user-friendly way in the respective phase.

The rigid separation of the development areas from production and all subsequent areas is to be eliminated through an iterative process. This involves constant iteration between pre-development, product engineering, process engineering and production. The product is to be continuously improved over time. This is accomplished through an improvement process that incorporates data from the production, use and end-of-life phases from several generations as feedback in the iterative part of the product lifecycle. An iteration can take the form of the introduction of a new variant or a new generation, as well as through a continuous improvement process. The product lifecycle continues to start with pre-development and runs through the phases to end-of-life. The iterations in the product lifecycle are shown schematically in Figure 39.

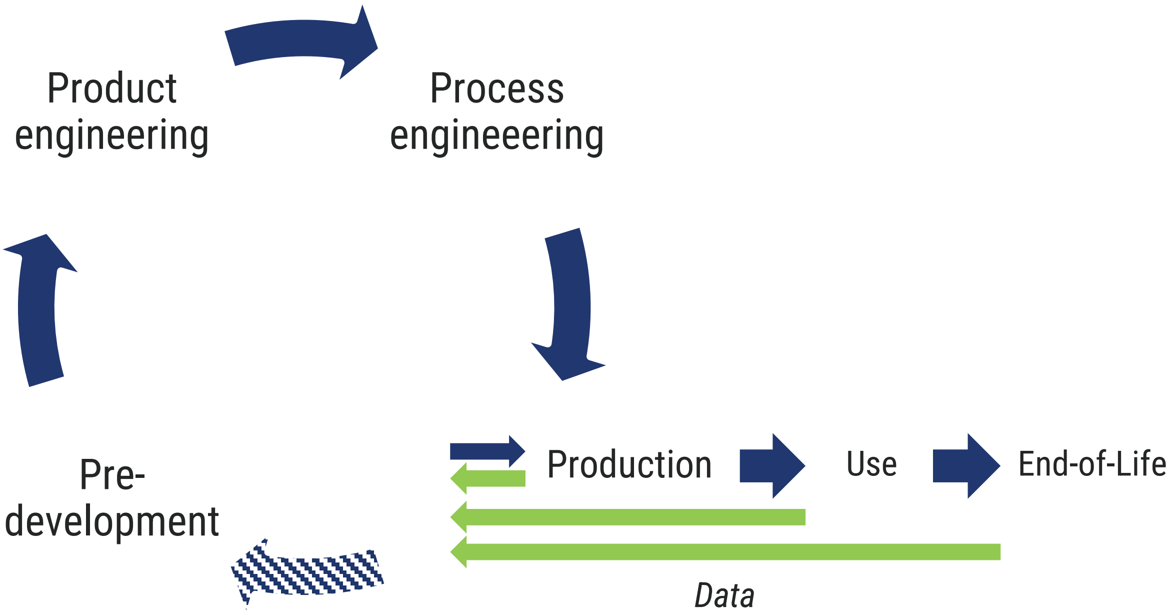


Figure 39: Schematic illustration of the iteration in a product lifecycle.

An iteration loop is difficult to depict in a phase model. The representation in a phase model also does not consider that iterations can also take place earlier than in the production phase. For this reason, the model can also be provided with several layers analogous to the iPeM of (Albers et al., 2016). In this case, each level would stand for a new variant, generation or version as shown in Figure 40.

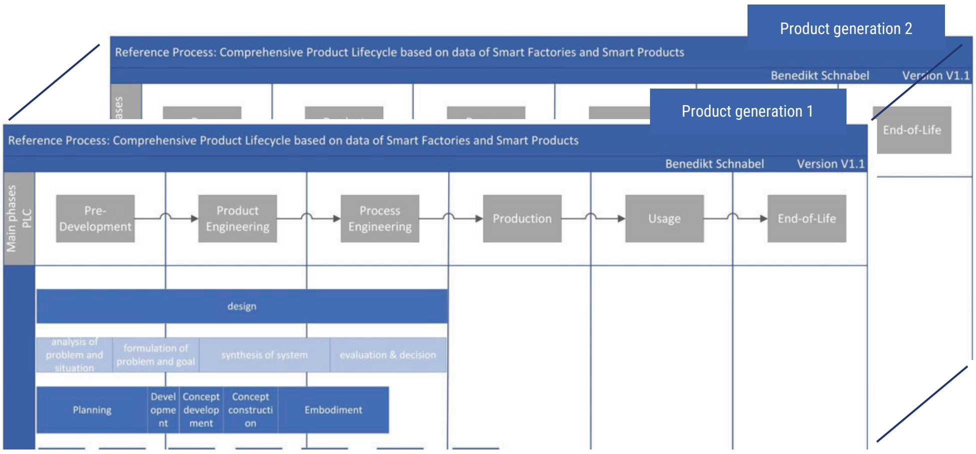


Figure 40: Schematic illustration of multi-layer view of the reference process.

However, the multi-layer view makes the model complex and difficult to apply. For this reason, a line is inserted that shows in which phase other generations, variants or versions are currently found.

The adapted reference process is shown in Figure 41. In the adapted reference process, the product lifecycle database is located in a green shape, and for the illustration of other phases, orange rhombuses with example data are used.

Sources:
[1] Feldhusen, J., & Grote, K.-H. (2013). *Pahl/Beitz Konstruktionslehre*, pp 21-23. Springer.
[2] Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP*, *50*, 100-105. https://doi.org/10.1016/j.procir.2016.04.168
[3] Niemann, J., & Pisla, A. (2021). *Life-Cycle Management of Machines and Mechanisms*, pp.17-47. Springer.

Figure 41: Optimised reference process for the comprehensive product lifecycle based on (Albers et al., 2016, p. 5; Feldhusen & Grote, 2013a, pp. 22-23; Niemann & Pisla, 2021, p. 58).

5.3 Implementation of findings from cause-and-effect relationships

The main adjustments to the reference process are made in this Section. In the process, the cause-and-effect relationships and the resulting data streams are integrated into the reference process. It is essential to allocate the data streams not only to the main phases but also to the processes. A detailed allocation takes place in this step. It is necessary to consider for each phase which data is needed, and which is created. The Figure 35, in which the data streams are shown on the basis of cause-and-effect relationships, is used as a guidance. Wherever there is a process flow, data is transferred from the previous process to the subsequent process of the current generation.

If data is generated for one of the following main phases, this is represented via the product lifecycle database. Likewise, the data flow for subsequent generations takes place via the product lifecycle database. The background of this is that all data generated in one product lifecycle is stored in a database and can be used for all subsequent product lifecycles. For this reason, the database is also represented across all phases and all product lifecycles.

Based on the cause-and-effect relationships, several process-specific adjustments were made. In the first step, the processes for building the prototypes were moved to the end of the modelling of the principle solution and embodiment in pre-development and product engineering. The final phase for building the prototypes takes place at the start of production. This is the case when production has been set up or adapted, and the first components can be manufactured on it. Although these components are prototypes, they are already close to the series production status. These components are also used to check whether they can be produced.

Furthermore, the validation and verification processes have been adapted to every main phase. This is the case because prototypes, the entire product or process sequences can be tested in each phase. Moreover, it has the advantage that the product or processes can be tested at the end of the product lifecycle, providing important feedback for subsequent generations.

Since the reference processes do not depict a process engineering phase, a phase for developing or adapting the production environment was added in this step. This is comparable to general production planning or process planning. It is placed in the main process engineering phase and runs parallel to the product design phase. This parallelisation is important because the product could still be adapted depending on the production environment. For this reason, close interaction is necessary.

The decommissioning analysis is also adapted and runs in parallel to the design of the principle solution, but in a shortened format. This change has been implemented in pre-development, product engineering and process engineering. The parallelisation is necessary because adjustments can be made to the product throughout the design phase that affects its ability to be remanufactured, recycled, or reused.

The analysis of the utilisation of the product is carried out in parallel with the modelling of the principal solution. This allows the construction and embodiment of the product based on its analysed utilisation. Also, the product's utilisation can be analysed and checked against the specifications at the end of the pre-development and product engineering phases. This provides a basis for validation and verification. During validation and verification in pre-development and product engineering, the use environments or the use cases can be enhanced for realistic testing.

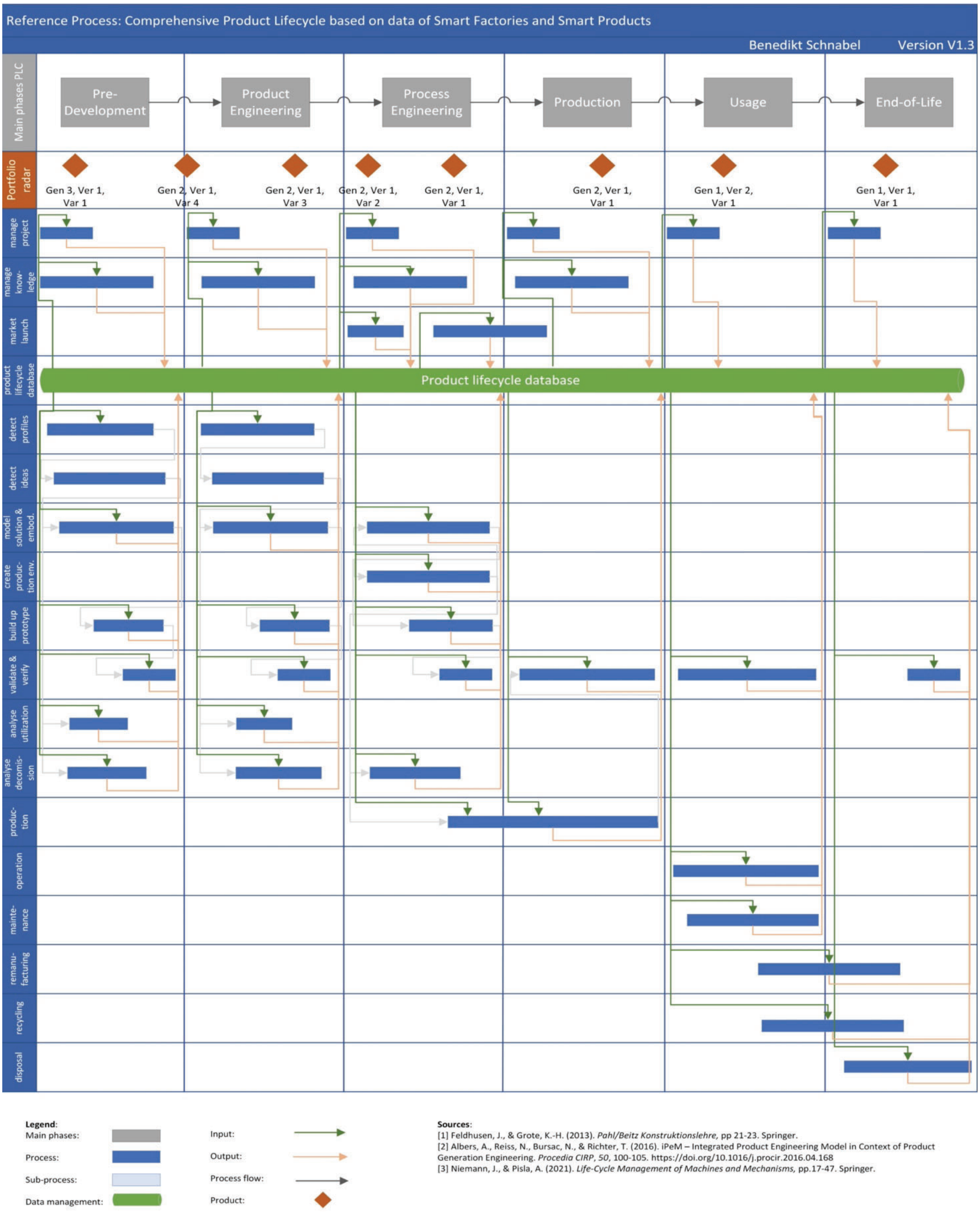
As the project management must be carried out throughout the entire product lifecycle, the corresponding phases have been inserted into all main phases. In this way, the project management keeps an overview of the use and end-of-life phases and can actively steer feedback from them and use them in the next generation.

In addition, the processes of the product engineering process, according to Feldhusen & Grote, were merged with the processes of iPeM. The planning phase for the product, variant or generation is included as a sub-process in managing knowledge and managing the project. Furthermore, the processes of development, concept development, concept construction and embodiment are to be understood as sub-processes of model principle solution. As a result, these resolve duplications and contradictions and makes the phases more user-friendly to design and manage the product based on the cause-and-effect relationships.

In the context of reducing duplication and implementing cause-and-effect relationships, the design phase of the product lifecycle, according to Niemann & Pisla, is removed. This phase is understood as a superordinate phase from pre-development to process engineering and is represented by more detailed phases.

Since end-of-life involves different processes for upgrading the product depending on the strategy, this phase was divided into reuse and remanufacturing. This is more suitable for the circular economy strategy and reflects the effects of end-of-life.

The adjusted product lifecycle is shown in Figure 42. To improve the overview, subprocesses are not shown. The structure of the product lifecycle corresponds to the usual structure but has been restructured to improve clarity. In the beginning, the six main phases are presented. Then the manage project, manage knowledge and market launch can be formed into organisational processes. The product lifecycle database is at the centre of Figure 42, as this is the core of the i^{2}PLM model. Data streams come from this database as input to specific processes; conversely, data streams come from processes as output to the database. As a result, information is exchanged across the lifecycle, which is represented by orange and green arrows at the corresponding processes. In addition, there are also process flows within the lifecycle that are driven by data. Grey arrows represent these flows. The multi-layer view is not shown in Figure 42 for clarity but is an integral part of the overall model.



Sources:
[1] Feldhusen, J., & Grote, K.-H. (2013). *Pahl/Beitz Konstruktionslehre*, pp 21-23. Springer.
[2] Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP, 50*, 100-105. https://doi.org/10.1016/j.procir.2016.04.168
[3] Niemann, J., & Pisla, A. (2021). *Life-Cycle Management of Machines and Mechanisms*, pp.17-47. Springer.

Figure 42: Product lifecycle with implemented findings of cause-and-effect relationships based on (Albers et al., 2016, p. 5; Feldhusen & Grote, 2013a, pp. 22-23; Niemann & Pisla, 2021, p. 58).

5.4 Further optimisations

In this step, the applied product lifecycle is further optimised, and data is placed in the core of the model. In order to make the best use of data, a fundamental data strategy must be anchored in the entire product lifecycle. The processes related to the data strategy are called manage data in the model and are based on the core components of the framework for big data-driven product lifecycle management by (Zhang et al., 2017, p. 233). These start with defining what data is to be collected over the product lifecycle and how they are to be collected. Structured, semi-structured and unstructured data can be relevant in each phase of the product lifecycle. The next step is to develop and integrate the sensor technology for the product or production and integrate it into the lifecycle processes. For example, data can be collected via smart sensors, tags, smart meters or other devices, but these must first be developed or adapted to the use case. Then, data is generated, processed, and stored. Real-time and non-real-time data is collected, cleansed, reduced, transformed, and stored depending on its type. This data is then used for analyses and to optimise the product and processes. For example, various data mining methods such as clustering, classification or product design improvement can be carried out. From the results, improvements are applied to the entire product lifecycle in the next step. For instance, the product design or manufacturing processes can be improved in the development phases based on these results; predictable maintenance can be carried out in the use phase, or an improvement in reusability can be made in the end-of-life phase (Zhang et al., 2017, p. 233).

In addition, knowledge management was extended to the use and end-of-life phase. As a result, there is also a process that actively tracks the use phase and derives knowledge from it. This also provides knowledge for service, maintenance and end-of-life strategies. Figure 43 shows a part of the product lifecycle with the implemented changes in the manage data and manage knowledge processes.

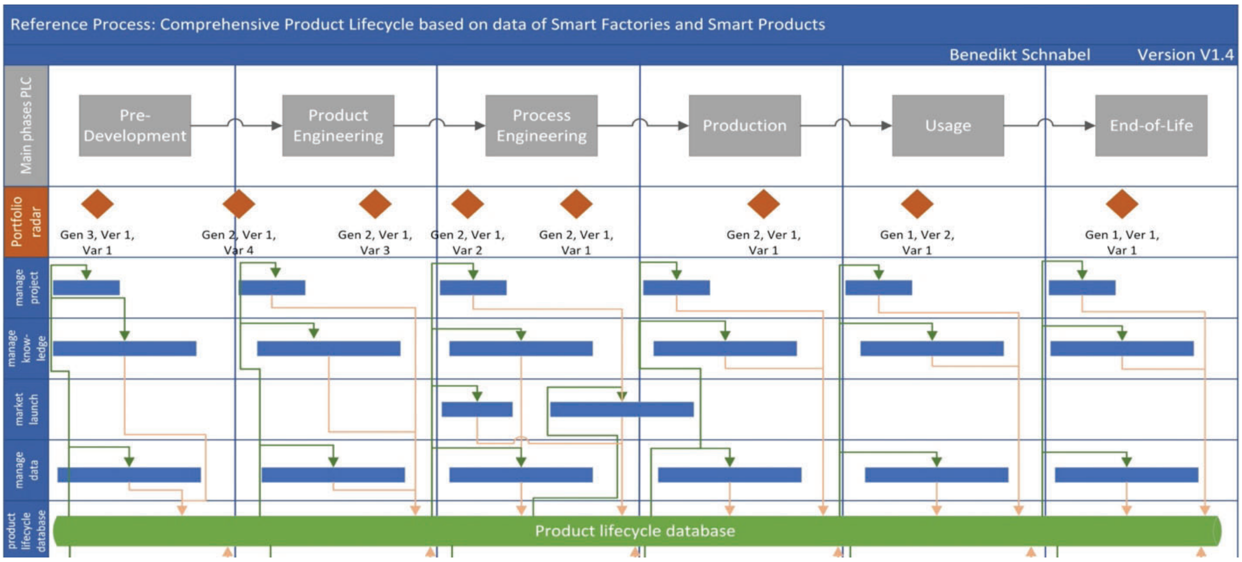


Figure 43: Further optimised product lifecycle based on (Albers et al., 2016, p. 5; Feldhusen & Grote, 2013a, pp. 22-23; Niemann & Pisla, 2021, p. 58).

5.5 The new integrated and intelligent product lifecycle management i^{2}PLM

The new integrated and intelligent product lifecycle i²PLM consists of six components and is structured as a phase model. The six components are described and detailed in the following Sections 5.5.1-5.5.6 and are shown in the following schematic Figure 44.

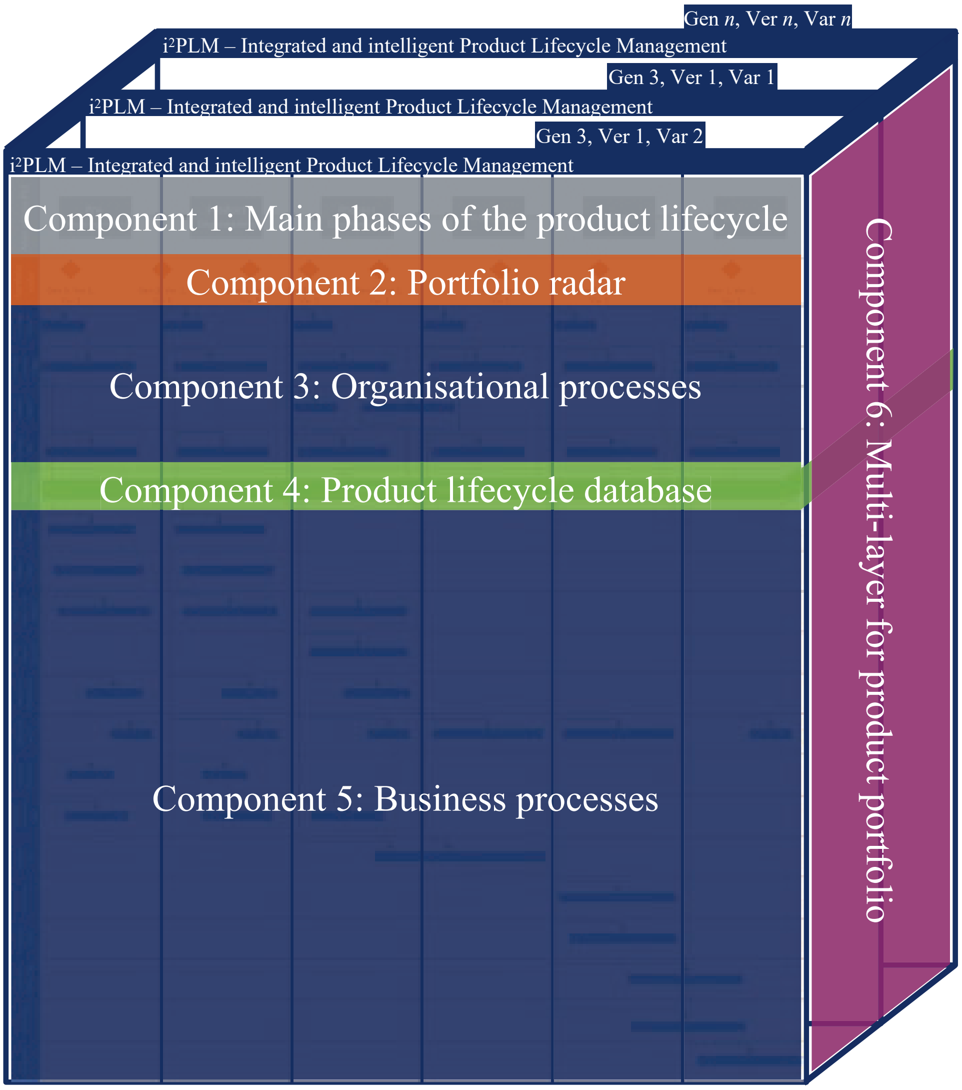


Figure 44: Structure of the i^{2}PLM.

The first component serves as a classification in the product lifecycle and represents the *main phases* of a typical product lifecycle. The phases range from pre-development to end-of-life.

The second component, *portfolio radar*, provides an overview of the product portfolio in the company. This component shows which phase of the product lifecycle the other products are currently in. A distinction is made between generations, versions and variants. The current status is shown as a rhombus and serves as orientation in the overall context. An example of a use case would be in the product engineering phase. For the functional development or validation of the product, user behaviour from other products can be taken as a basis. The portfolio radar then shows which products are currently in the use phase.

The third component is *organisational processes*, which stand for project management, knowledge management, market introduction and data management. They serve more as support processes for the business processes.

The fourth component is the core of the model and includes the *product lifecycle database*. On the one hand, this database contains data from all products and, on the other hand, it represents the data streams as well as the processing and analysis of the data.

The fifth component is *business processes*. All processes that are necessary for a product lifecycle are anchored in this component. These processes range from the development of ideas, construction and design, validation, production, tot he use and end-of-life strategies.

The sixth component represents the *multi-layer* of the model. Since, in most cases, a product consists of several generations, versions and variants, and these are in different phases of the product lifecycle, layers are represented for each product type. The current product type is shown at the top of each layer.

5.5.1 Component 1: Main phases of the product lifecycle

The first component of i²PLM provides the user with guidance on the main phases of a product lifecycle. The phases serve as the headings of the columns. The component is shown in the following Figure 45. The product lifecycle is divided into six phases. It begins with the pre-development phase, in which the product idea is generated. In addition to the technology development, the implementation of the product is initiated, and its feasibility is tested in this phase. This is followed by product engineering. Within this phase, the idea is implemented in a developed product. For this purpose, the concept is generated, and the product is constructed. Furthermore, prototypes are created and tested. The next phase is process development, in which the processes for manufacturing the product and for logistics are developed. In this phase, the product can also be adapted again. When the production processes are planned, the production phase follows. In the production phase, components are manufactured and assembled into the final product. The product is then delivered to the customer and used in the use phase. This continues until the product is no longer used for its original function, for example, due to a defect, and thus it enters the end-of-life phase. In the end-of-life phase, the product can either be directly reused, remanufactured, recycled or disposed of.

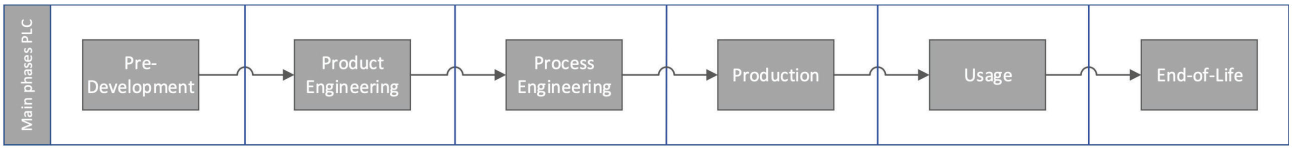


Figure 45: Component 1: Main phases of the i²PLM.

5.5.2 Component 2: Portfolio radar

The portfolio radar illustrates an additional support for all employees of the company, from the planners of the product lifecycle to the employees from the respective phases. The component is shown in Figure 46.

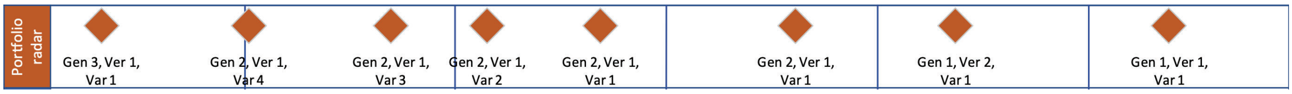


Figure 46: Component 2: Portfolio radar.

The portfolio radar provides the user an overview of the current status of different product types. Since in product families with several generations, there are many different product types at the same time, the overview is frequently missing, whereby the transfer and learning from other product types suffer and mistakes are made repeatedly. Through the radar, for example, an employee from product engineering is able to see which product type is currently in use and read out the data from this product.

It is crucial to update the portfolio radar continuously. Therefore, central storage in the cloud with the implementation of tools is recommended.

5.5.3 Component 3: Organisational processes

In the third component, all organisational processes are listed. These are divided into project management, knowledge management, market launch and data management. The Figure 47 shows the respective phases, including the main phases for reference.

Project management lists all activities that contribute organisationally to the administration of the project. This starts in pre-development, where on the one hand, the entire product lifecycle is roughly planned as a project. Framework conditions for the respective phases are defined, as well as their target dates and budgets. On the other hand, pre-development is finely planned, and targets and deadlines are set for this phase. In the subsequent phases, the rough project planning is translated to the phases and fine-tuned. The resources from the different departments are planned, and the progress, as well as the achievement of objectives, are evaluated. In order to translate the rough project planning to the phases and to evaluate the current progress, data from the product lifecycle database is needed. In addition, lessons learnt should be made in each phase, which is additionally stored in this database.

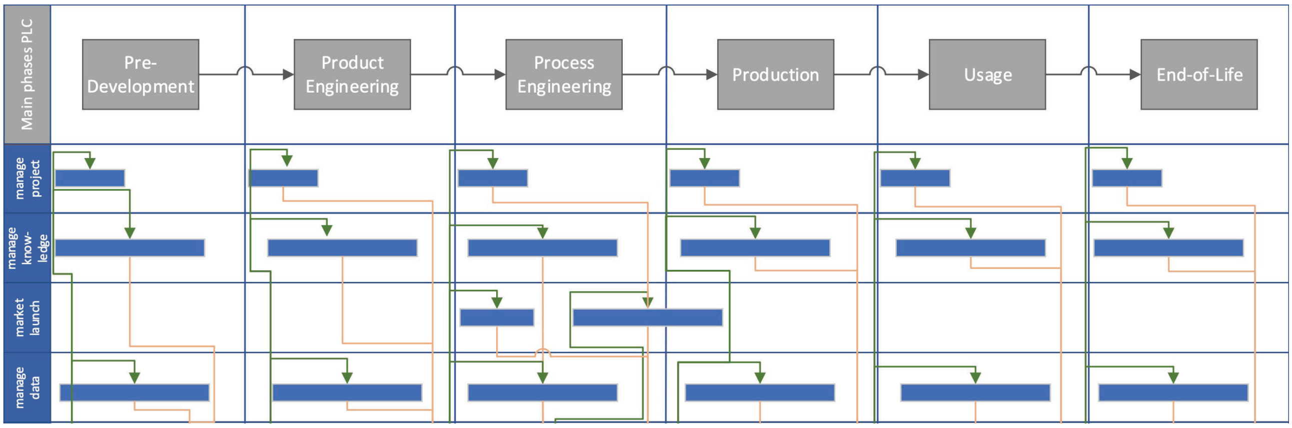


Figure 47: Component 3: Organisational processes.

Knowledge management is responsible for storing knowledge from the phases and making it available in other situations. It is closely linked to the product lifecycle database, because all knowledge that is generated should be stored and made available in the database. This allows knowledge to be shared across product types. In order for this to happen, the knowledge management for the phase has to be planned at the beginning of each phase. This involves determining which paths and sub-processes can be used to transfer knowledge to the knowledge database and how it can be retrieved from there.

The market launch represents the organisational processes around the introduction of the product. On the one hand, planned figures for the number of units are determined, and the production runtime on the other. In addition, all processes that are necessary from a sales perspective before the sale of the product and the planning of pre-series components for pre-series production are located in this section.

Data management is a signification part of the new i²PLM. Since data forms the basis of the data-driven product lifecycle, planning processes are needed for data generation, analysis and storage. For this reason, data management is also part of every phase of the product lifecycle. Activities of data management start in pre-development, where a holistic data strategy for the product is developed and thus lays a foundation. The data strategy includes defining data types that can be used as a basis for engineering, the process how this data is processed, which data should be recorded for product improvement, and how it is stored. In addition, existing functions between variables are transferred to the use case or newly developed on the basis of knowledge.

In the product engineering phase, technologies are used to develop processes for recording data of the product. All variables from relevant functions should be detectable. For example, concepts for sensors in the product are developed in this phase for the production, use, and end-of-life phases.

Within the process engineering phase, technologies for recording data in the smart factory are developed and integrated. For example, the sensors used in the smart factory to check the quality of the product are defined.

In the production, use and end-of-life phases, data management is used to manage the recording and analysis of data. These analyses can trigger a new type of product. In the end-of-life phase, data from product and process engineering is used to remanufacture, recycle or dispose of the product. Data is also recorded for the respective scenarios, such as the ability to remanufacture the product. Another topic that should be addressed in the context of data management is data security. For this reason, the Security Office Centre proposed by (Ferencz et al., 2021, p. 245) should be located within this phase as the department responsible for data security in order to take preventive steps to minimise vulnerabilities and to monitor security.

5.5.4 Component 4: Product lifecycle database

As a central database, the product lifecycle database is responsible for storing, analysing and making available data on the entire product lifecycle. The database covers all product types. The following Sections 5.5.4.1 – 5.5.4.4 describe the analytics and functions for lifecycle data, exchange of data, and i^{2}PLM software tools.

5.5.4.1 Analytics of lifecycle data

In order to use the amount of data, a system must first analyse it. There are many ways to analyse the data. (Niemann & Pisla, 2021, p. 58) summarise these ways in four categories for product lifecycle management. There is descriptive analytics, in which the data is analysed in pure form and presented in a usable way. In diagnostic analytics, causes and developments are analysed from the data. In predictive analytics, developments in the future are predicted from the data. Finally, in prescriptive analytics, forecasts and optimisations, as well as their effects, are suggested. Depending on the application in i²PLM, one should select the most suitable analysis category.

However, in order for this data to be available in its entirety, the storage of the data should be considered. Data can be generated at any phase of the product lifecycle. To avoid isolated solutions, a uniform data platform should be used. For example, a cloud would be suitable, in which each department can import, and export data. It is also essential that the applications the employees work with also function with this cloud and can exchange data (Niemann & Pisla, 2021, pp. 58-60).

5.5.4.2 Functions for lifecycle data

Since data can be used differently at each point in the product lifecycle and, in addition, data is created at different points in the product lifecycle, a concept must be created that describes these relationships. In a product lifecycle, data can be interconnected in different ways. This is a component for adapting the i²PLM to the use case. Since every company and product has specifications, the first step should be to adopt the cause-and-effect relationships from Chapter 4. For this, the interrelationships in the company should be identified. However, the process is never finished. New products, technologies, and knowledge can lead to new correlations being identified, or old ones becoming useless. In this process, the knowledge gained should be incorporated iteratively.

In the next step, functions emerge from the cause-and-effect relationships, from which data streams can be developed. For example, a temperature sensor in production can be the trigger for component changes in development, or data on the feasibility of ideas from product engineering can flow into improving pre-development. For this, however, it is still important that the data in a product lifecycle comply with a standard in order to be usable in every phase. Many associations are currently establishing standards. For instance, the International Federation for Information Processing lays an important foundation for standards.

5.5.4.3 Data exchange

The required data streams include the data exchange and are derived based on the functions in the next step. Data streams always take place where functions connect different parameters. The data streams of the product lifecycle database are shown in Section *4.3.1 Data streams in a product lifecycle of a smart customisable product family* at phase level. Within this section, the main data streams are also shown across generations. The data streams are used to set up the database. As shown in Figure 35, most of the phases are connected with each other, which emphasises the importance of a database in the form of a cloud. To illustrate in which process in the phase data flows in and which process delivers data as output, the data streams are integrated into i²PLM and are shown as arrows. The following Figure 48 shows an example of a section of the i²PLM in which data streams are visible. The other data streams in the i²PLM are created in a similar way to this illustration.

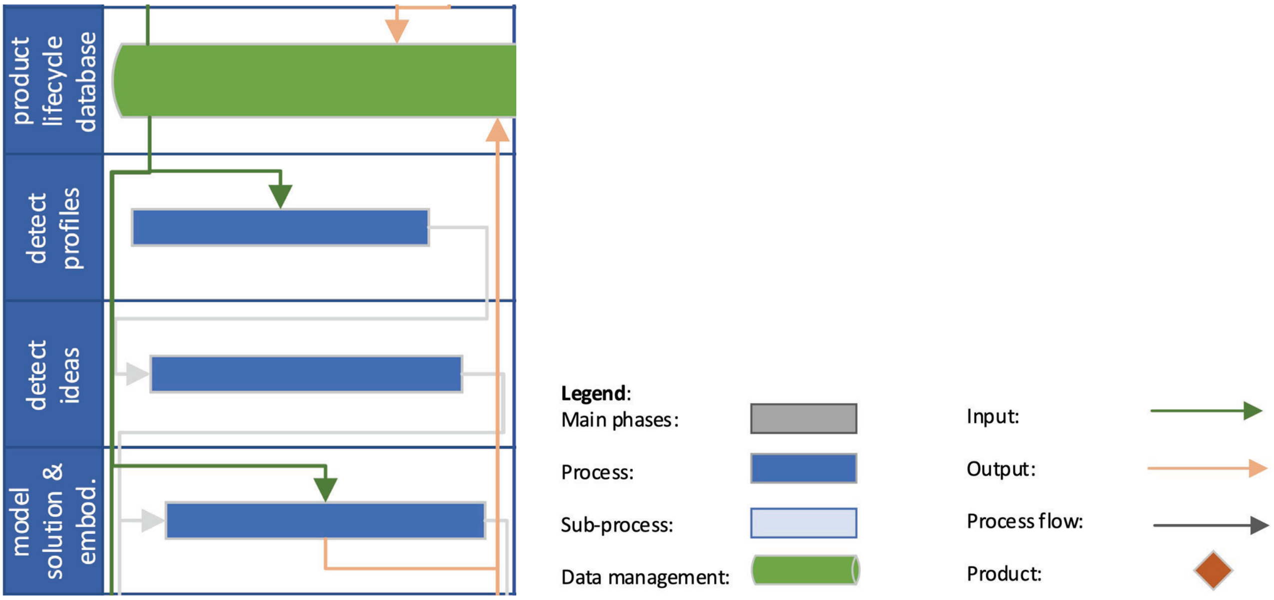


Figure 48: Example data streams of i²PLM.

The data streams should be customisable, since the world of digitalisation and companies themselves continue to develop and new data streams can emerge. Through customisability, new functions can be integrated and implemented more quickly (Niemann & Pisla, 2021, pp. 62-63).

5.5.4.4 i²PLM Software Tools

There is a wide range of tools for using functions from the database. The tools can be used in different areas of the company. There are tools for data and document management through which the recorded data can be distributed. This correlates with knowledge management, which facilitates collaboration between employees with the help of tools. From an organisational point of view, it is also essential to have tools for project management in which the data from the phases and their status are visible. To link the recorded data with quality management, there are also tools that evaluate production and use data and identify errors.

Furthermore, especially in product and process engineering, it is important to integrate the database with computer aided design (CAD) in order to be able to use data for design and to make design data accessible to other parties. In the process engineering and production phase, asset management tools are particularly important to map the existing production facilities as a Digital Twin. In addition, in the course of the circular economy, there are tools for the environment, health and safety in the company.

In order to develop products more quickly, qualitatively and efficiently and to incorporate feedback from previous generations and variants, the novel i²PLM-tool is developed as part of this work. The focus is on analysing data from the production, use, and end-of-life phases in the pre-development, product and process engineering phase.

The Figure 49 shows the process flow of the i^{2}PLM-tool. The process starts with the user choosing between manual and automated problem analysis. The user also selects data types to be analysed in the automated problem analysis. This data is transferred from the database and analysed in the next step. With the help of the four different analysis methods, problems in the data sets can be identified. In addition, the user also has the possibility to select problem classes and problems of the product manually. With the help of functions that are based on cause-and-effect relationships, possible causes are derived from the problems. Behind each cause are proposed solutions, and the user can select from these. After selecting the solution, the associated parameters are automatically changed via the cloud. For example, when changing a design parameter, possible solutions can be proposed via generative design, and a new design can be created.

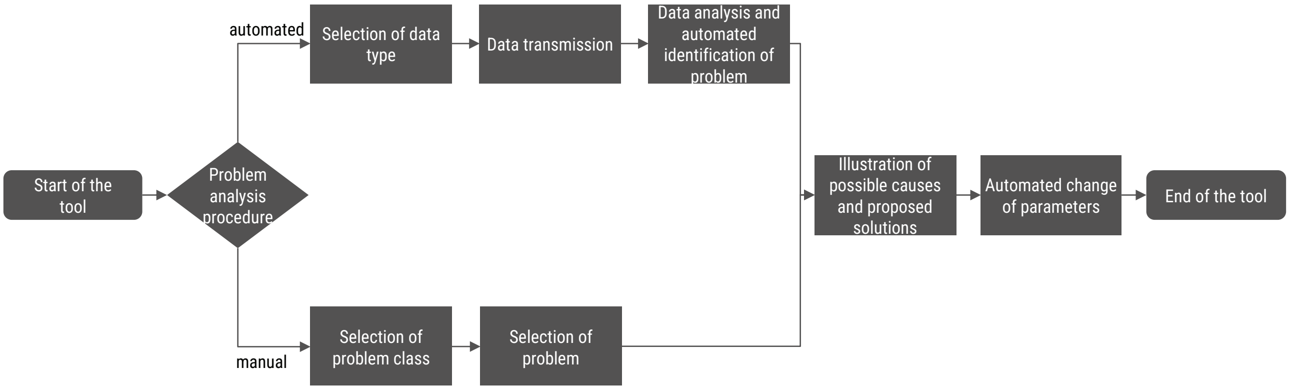


Figure 49: Process flow of i^{2}PLM Tool.

The following figure also shows the input mask of the i^{2}PLM tool. The tool implements manual and automated cause identification. The upper two selection fields are used for the manual identification of the problem. With the upload file & read function, data can be uploaded for automated analysis. The user can then analyse the data and receives proposals for causes and solutions.

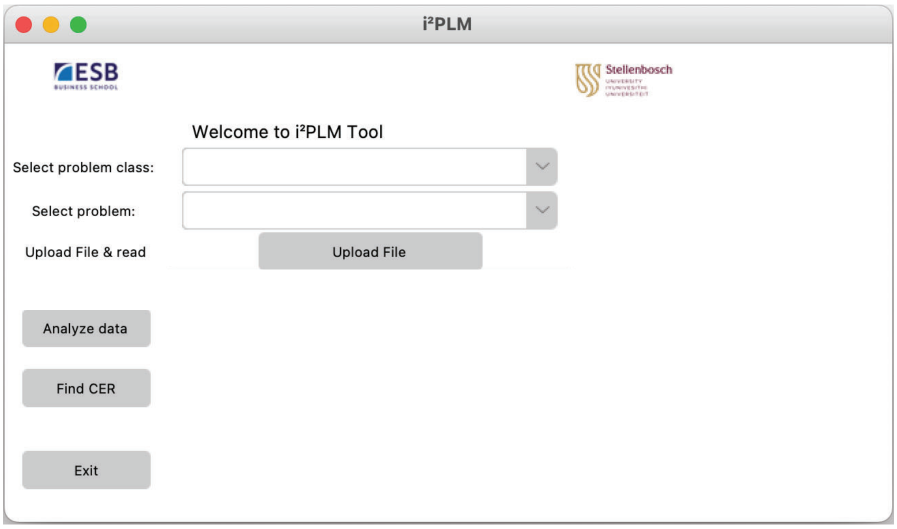


Figure 50: The user interface of the i^{2}PLM-tool.

5.5.5 Component 5: Business processes

The business processes represent all activities directly linked the product. These include the idea generation and development of the product, the production, the use phase and the various end-of-life strategies. Since the processes depend on the respective phase of the product lifecycle and are linked to other processes from the phase, the processes are described below in a phase-oriented way.

The business processes are shown in Figure 51. In order to be able to assign the processes to the main phases, these have also been added as column headings. In general, the processes are structured according to their order in the product lifecycle. It starts with processes for the (pre-)development phase and ends with processes for the end-of-life strategy.

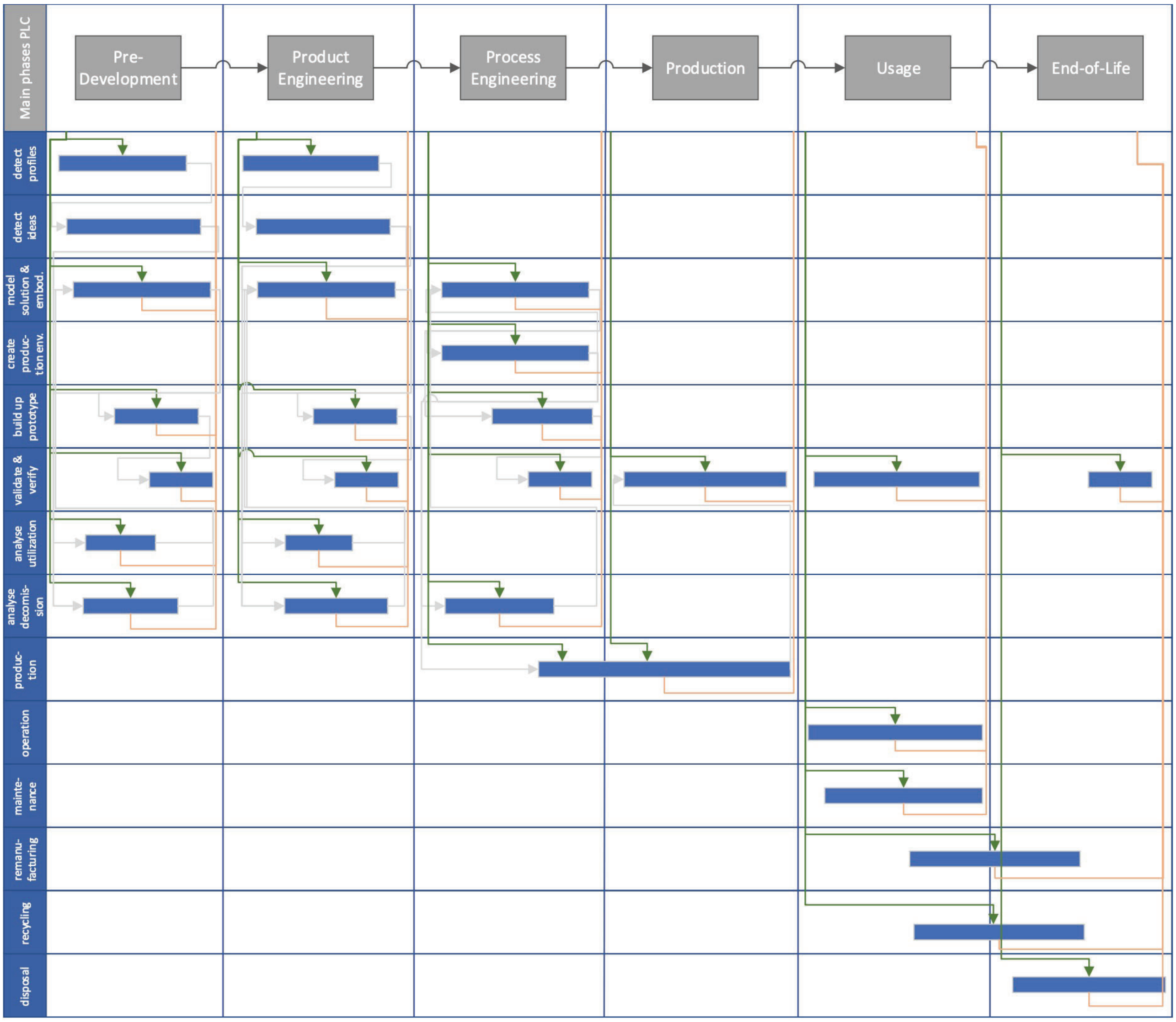


Figure 51: Component 5: Business processes.

5.5.5.1 Pre-development

In the pre-development phase, the processes detect profiles, detect ideas, model principle solution & embodiment, built up prototype, validate & verify, analyse utilisation and analyse decommission are located. In the beginning, the product users are analysed in the detect profiles process and user profiles are created for the product. Furthermore, the utilisation of products from previous product types is analysed. In these processes, data mainly from the use phase of previous product types flow in. These can be, for example, product quality data, use data and other Key Performance Indicators (KPIs). Potentials are discovered from this use data and use cases are created that form the basis for idea detection in the next step.

In the *idea detection* process, product, concept and production ideas are generated from these use cases. The scope depends on whether it is a new version, a variant or a generation. In the next step, a rough solution is modelled and embodied from the ideas. Framework conditions from the subsequent phases already flow in. For example, a framework condition from process engineering can ensure that the idea is also producible. Once the idea has been implemented as a design, a first prototype is built, which is still far away from the final product, but it nevertheless allows conclusions to be drawn.

Conclusions are generated by *validating and verifying* the prototype. To ensure a realistic evaluation of the prototype, the evaluation cases are also fed with use data. This forms the basis for the simulative evaluation of prototypes.

In order to include the core ideas of the circular economy in the early phase and thus set the course right from the start, the decommissioning capability is analysed. This is done on the one hand based on the design of the product and on the other hand, through data from the end-of-life phase of previous products.

The results of design, prototyping, validation & verification, utilisation and disposal are fed into the product lifecycle database.

5.5.5.2 Product engineering

The product engineering phase starts with *detecting profiles* from the pre-development being revised and detailed through the prototype tests and the adapted use cases. This is done with the *analysis of the utilisation* on this basis. The adapted profiles and utilisations are then used as a basis for *idea generation*, where the idea from pre-development is adapted and the specifications are more detailed. Based on this and with the conceptual design from the pre-development, the product is designed and constructed. The design and design processes are based on systems engineering. Within this process, the procedure is divided into the *concept development*, and *concept construction & embodiment*.

Afterwards, the constructed product is *validated and verified* either at component level and at product level, or in some cases directly at product level. The validation strategy depends on the product and can be iterative. In addition, the product should also be tested for *decommissioning* capability. This is carried out through close cooperation between the processes *model principle solution & embodiment* and *analyse decommission*.

The designed product, the results from prototyping, the validation and verification results, as well as the use cases and decommissioning strategy are stored in the product lifecycle database.

5.5.5.3 Process Engineering

In process engineering, the focus is on how the product can be produced. Here, the customer's profiles and the use cases are not needed anymore. The two main processes are *model solution & embodiment* and *create production environment*. They are closely linked because, on the one hand, the product often has to be adapted to be more producible, and, on the other hand, the production must be adapted to the product. It is important to check what effect product changes have on production and vice versa. In order to achieve a balance and to cause as few changes to the product and production as possible, both processes should work together iteratively. Also, the logistics planning is part of the *creation of the production environment*. In addition, product changes and assembly processes can influence end-of-life strategies. For example, products can be specially built what makes them easily repairable. Once the product and production are designed, prototypes are built, which are *validated and verified*. In addition, the pre-series production starts after successful tests in production.

From the processes model solution & embodiment, create production environment, built up prototype, validate & verify and the analysis of the decommission, data for subsequent phases and subsequent product types flow into the product lifecycle database.

5.5.5.4 Production

In the production phase, the product is manufactured and assembled in a smart factory. In the process, data is collected during production that provides conclusions about the KPIs of the smart factory, the quality of the product and the manufacturing processes. This results in many potentials that can be implemented in subsequent generations. As a result, production is constantly improving. In addition, components and products from production are used for *validation and verification* to check the quality of the manufactured products. The goal of the *production* phase is to generate a product that can be delivered to the customer and fulfils all functions.

For continuous improvement, respective processes should be implemented that can adjust the production environment based on the data collected in series production. These data flow in the process engineering processes.

The production phase ends with the last built product of the corresponding product type.

5.5.5.5 Use phase

In the use phase, the product is at the customer's side and thus in the *operation* process. The smart product collects customer data during the use of the product. Which data is collected depends on which sensors, tags and other devices are planned and integrated in the product in the previous phases. In addition, there should be an indirect path through which customer satisfaction, product defects and other variables that cannot be measured directly via sensors can be retrieved. In this phase, *verification and validation* is also implemented through direct product use. This process can then be compared with the previous validation and verification processes. This can lead to an improvement in *validation & verification* for subsequent generations as a more realistic test environment can be established.

In addition, maintenance measures are also carried out in the use phase in order to extend the lifetime. These activities are usually necessary when there is a defect in the product. The data on defects and their causes should be collected and can yield potential for new product types and new cause-and-effect relationships in due course.

Furthermore, the end-of-life strategy direct reuse also takes place in the use phase. In this case, the product is transferred to a second user when it is no longer needed by the first user. This also generates relevant data, since on the one hand different types of applications are observed, and, on the other, different applications can exist.

Remanufacturing and recycling are to be considered between the use phase and the end-of-life phase. In remanufacturing, components of a product are exchanged in order to either fulfil the previous functions or to obtain a new range of functions via an upgrade. In both processes, the extent to which the interchangeability and modularity of the products has been implemented can be checked. This serves as a basis for concept design and for analysing the decommissioning of subsequent product types.

5.5.5.6 End-of-Life

The lifecycle of the product ends with disposal. Within this phase, the product is disposed of either by the customer himself or by the company. Disposal breaks the circular economy because no part of the product is used any further. Nevertheless, important data can still be collected through the *verification and validation* of the end-of-life strategies. The reason for the disposal of the product is disposed of can be documented. For example, this may be because the functions are no longer needed, there is a defect that cannot be repaired, or the materials cannot be recycled. In order to better implement the circular economy in the next product types, the data can be transferred and used as requirements in the following product developments.

5.5.6 Component 6: Multi-layer for product portfolio

Since most products are developed in generations and these generations have variants and versions, a multi-layer view has been integrated into the i²PLM. The multi-layer component is shown in the following Figure 52. It is based on the multi-layer view of iPeM but does not look at the process model from different angles like production system or strategy.

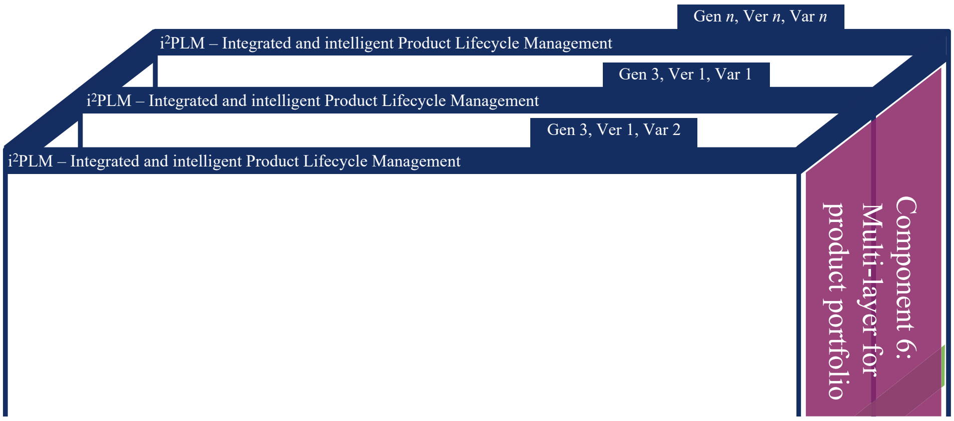


Figure 52: Component 6: Multi-layer for product portfolio.

A new layer is generated with each new run of the product lifecycle. Every layer's structure is the same and includes the described components. This is the case when a new generation, variant or version is to be created. The multi-layer view is used to link the development phases with production, use, and end-of-life.

The layer view has the advantage that time deviations from the i²PLM can be transferred from previous product types to the current one. This allows the i²PLM to be iteratively adapted to individual products with individual process efforts.

5.6 Chapter summary

In this chapter, the novel integrated and intelligent Product Lifecycle Management i²PLM is created. The first step is the generation a reference process. Since iPeM meets all the requirements, it is used as the reference process. The reference process is extended to include the Product Engineering Process and the Product Life Cycle. In the Product Engineering Process, the phases of product and process development are focused on, and in the product lifecycle, the phases after the production phase are detailed. The three reference processes are combined into one reference process. In the following, the reference process is simplified and optimised with the help of the literature work from Chapter 3. After this basis is created, the data streams from Chapter 4, which are based on the identified cause-and-effect relationships, are incorporated into the product lifecycle. In the next step, the product lifecycle is optimised once again, resulting in the novel i²PLM. The i²PLM consists of six components, which are described in Section 5.5.

Chapter 6 Validation of the product lifecycle i²PLM

In this chapter, the novel product lifecycle is validated. The first step is to classify the validation and select the procedure. This is followed by a description of the experiment, showing the environment, the product, the production, processes, and its limitations. This is followed by the results of the validation.

6.1 Selection of the validation procedure

In order to be able to review the product lifecycle, it must be defined at the beginning whether validation, verification or evaluation will be carried out.

- **Verification** checks whether the proposed solution matches the original specification. For example, the question is asked whether the calculations are correct (Fenz & Ekelhart, 2010, pp. 58-63).
- **Validation** is the process of checking whether the proposed solution meets the expected requirements. The guiding question here would be whether the overall result is correct (Fenz & Ekelhart, 2010, pp. 58-63).
- The outcome of an **evaluation** is the determination of the significance, meaningfulness, value or condition of the proposed solution (Fenz & Ekelhart, 2010, pp. 58-63). An example question would be what environmental changes caused by the proposed solution can be detected.

Due to the respective verification patterns, this work will focus on validation. This is based on whether the product lifecycle as a whole is correct and applicable and whether it meets the expected requirements.

One method for validation is experimentation. The purpose of an experiment is the investigation in which a specific assumption or conjecture is specifically tested and either proven or disproven. An experiment was chosen to validate the developed product lifecycle. An experiment also has the advantages of being repeatable and, in most cases, practice oriented. A practice orientation is important because the validation is to check the applicability of the model.

6.2 Description of the experiment

In order to be able to carry out an experiment successfully and in a repeatable manner, the object of investigation and the procedure must be defined in advance.

A distinction is made between the experiment environment, product, production, business process, number of pieces and limitations.

6.2.1 Environment

Werk150 at Reutlingen University was chosen as the experimental environment. Werk150 is a research environment where the latest production and logistics technologies are developed and used. To ensure proximity to companies and to test use cases for the technologies, various products are manufactured in Werk150. On the one hand, this involves a pedal scooter, and, on the other, a modular, intelligent mobility box (Reutlingen-University, 2022). Based on the technological advantage, the realistic production environment and the industrial reference Werk150 represents an optimal environment for the experiment.

6.2.2 Product

The selection of the product is based on the product characteristics defined at the beginning, which are named in the following: The selected product must be part of a product family. It must be customisable and smart. It should reach at least level three of the smart products archetypes. This means that it has basic hardware for storing, processing and analysing data. In addition, it is connected to a network and it can send and receive data. The product also has sensors for predefined situations.

The modular intelligent mobility box (MIMB) is suitable as a basis product for the experiment. It is shown in Figure 53. The modular intelligent mobility box is the latest product for the Werk150. It consists of a basic module with a mini-computer and about 30 modules of which up to six can be combined according to the customer's needs. The product is able to communicate with the environment and to interact with other devices through integration into a network infrastructure. The product can collect data through sensors (e.g., temperature sensor, GPS sensor and presence detection modules). The data is stored and evaluated through an analysis tool. A rental model for the use of the box is to be offered to students at the university.

Figure 53: Prototype of modular intelligent mobility box (Kunz, 2022, p. 64).

For validation, the focus is limited to one of the modules. Since the lunchbox offers the possibility of customisation and can be found in smart products archetype class three due to its built-in sensors, it is used in a modified form for the experiment. The adjusted smart lunchbox is shown in the following Figure 54.

Figure 54: Smart Lunchbox CAD.

In order to validate the Smart Lunchbox in a realistic use phase, a particular use case is defined. The use case states that the Smart Lunchbox is to be leak-proof. During the use the sensor of the Smart Lunchbox measures the temperature inside. For the use case the Smart Lunchbox should keep chilled food fresh for one's way to work. This means that it keeps temperature below 15 *°C* for one hour after removal from the refrigerator. These features are also common in conventional lunchboxes (Bundesamt, 2016).

The lunchbox consists of the 3D-printed top and bottom, a temperature and humidity sensor, from

Milesight, a gateway from LoRaWan, and a velcro. The bill of material (BOM) of the product is shown in the appendix.

6.2.3 Production

The production of the Smart Lunchbox takes place at Werk150. To reduce complexity, only the smart lunchbox as a module is considered and not the entire modular intelligent mobility box. The production essentially requires a 3D printer and assembly workstations. The precedence graph is shown in Figure 55.

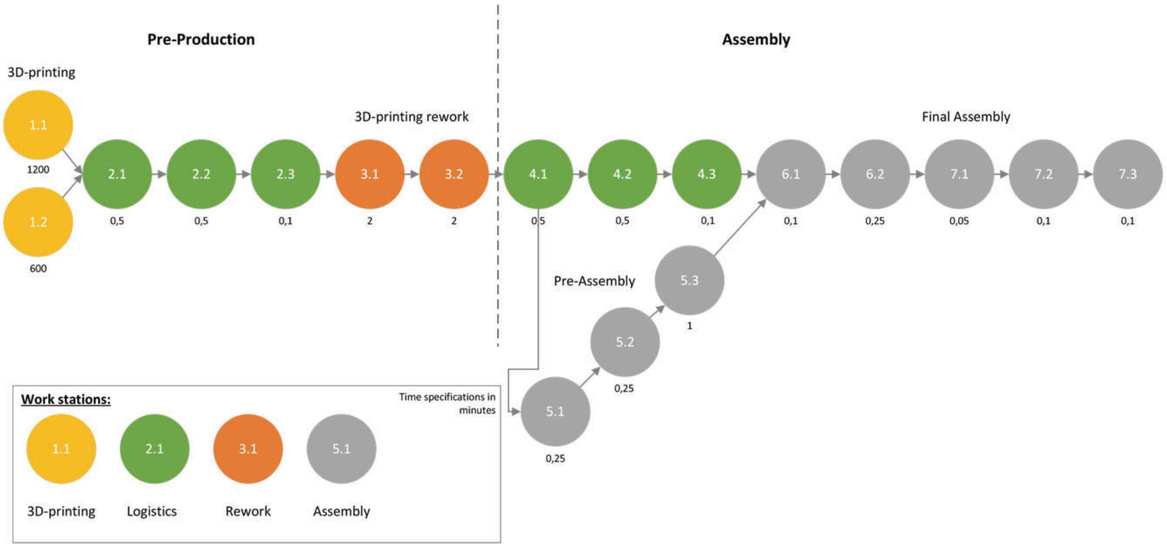


Figure 55: Precedence graph of Smart Lunchbox in Werk150.

The production starts with 3D printing the parts – shown with the yellow dots in Figure 55. Then the 3D printed parts are reworked. The sensor is attached to the lid with a secondary line while the second component is being cleaned. Afterwards all parts are assembled in the final assembly.

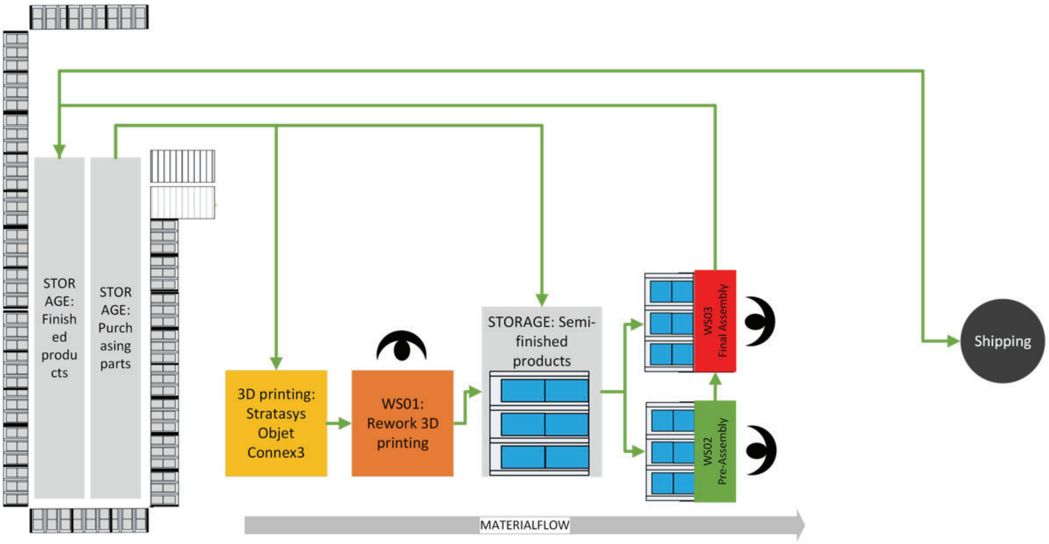


Figure 56: Production layout of Smart Lunchbox in Werk150.

The precedence graph is applied to the layout of Werk150 in the next step and thus the production system is designed with the material flow. In Figure 56, the following four work stations of production are shown: the Stratasys 3D printer, the 3D printing rework, the pre-assembly and the final assembly.

6.2.4 Business process

The newly developed product lifecycle is applied as a business process. Since the product and the production environment meet the requirements, it can be used for validation without modification in the experiment.

Applied to the use case, the following procedure illustrated in Figure 57 arises:

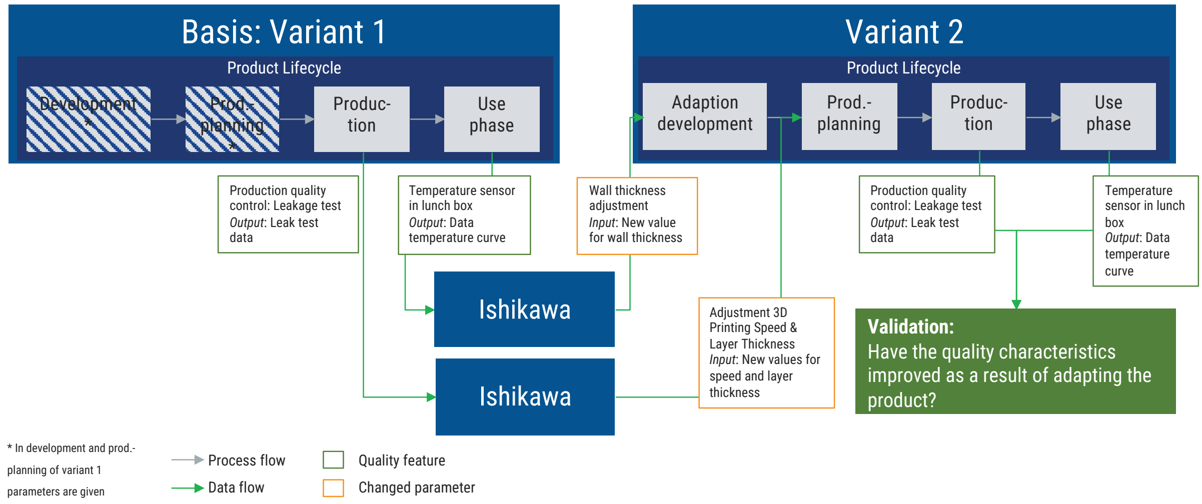


Figure 57: Schematic diagram of the experiment procedure.

In the first step, it is assumed that *Variant one* has already been developed and the production planning has already been carried out. This is followed by the production of the smart lunchbox in Werk150. During production, data is generated on the quality characteristic leak density in the quality control. The product is used by experiment participants in the use phase. In the use phase, temperature data is generated while carrying out the use cases. These data are converted into a temperature curve which flows into an Ishikawa and triggers product and production changes for the subsequent generation (*Variant two*).

Variant two is a customised smart lunchbox. The changes in the product engineering of *Variant two* are mainly incorporated by changing the wall thickness, as this significantly influences the temperature curve on the product side. In process engineering, information on 3D printing speed, layer height and part position result into requirements for the 3D printing process. The volume of the compartment changes based on a new simulated user requirement. Subsequently, the product is engineered, produced, and used. The same data types are recorded by the quality control and the sensor during the use phase. By repeatedly recording data, it is possible to indicate whether there has been an improvement between the variants or not.

6.2.5 Number of pieces and repetitions

In an experiment, it is important to find the right quantity of repetitions. A partial mass is used to represent the total mass. A partial mass is representative if it allows an accurate conclusion to be drawn about the population (Berekoven et al., 1989, p. 48). The quantity of both built components and conducted experiments depend on many different factors.

In order to determine the number of representative partial masses, a more differentiated consideration is required. A distinction can be made between the number of components (mass of the production study) and the number of users (mass of the utilisation study).

To determine the partial mass of the production figures, the full-factorial experimental design according to (Siebertz et al., 2017, pp. 6-7) is used. The statistical full-factorial experimental design offers a way to reduce the experimental effort which enables an investigation of many factors with reasonable effort. The first step is to determine the number of factors (n_f) that can be specifically changed. In this application, these are the part orientation (A) and material composition (B) of 3D printing. For the factors, levels (n_l) are selected in the next step. Since in this case, a production fault is to be specifically provoked, a high (+) and low (-) value is selected. The experimental effort is calculated according to the following formula:

$$n_r = {n_l}^{n_f} \tag{1}$$

This results in an experimental effort for this step amounting to four products to be built.

$$n_r = {n_l}^{n_f} = 2^2 = 4 \tag{2}$$

According to (Siebertz et al., 2017, pp. 6-7), the experimental plan is represented by a table in which all possible combinations of the stages and factors are shown. The experimental plan for this step is shown in the following Table 12.

To check the influence of the change in factors, the quality characteristic of the density of the lunchbox is used. During production, a quality control is carried out in which the product is divided into the defect categories "Product leaks - water leaks" and "Product is tight - no water leaks".

Table 12: Full-factorial experimental plan based on (Siebertz et al., 2017, pp. 6-7).

A	B	y_x
+	+	y_1
+	-	y_2
-	+	y_3
-	-	y_4

To find the right quantity of users that are representative of the user base, the Cochran formula for calculating sample sizes for smaller populations is used. The Cochran formula for sample size calculation of smaller populations is shown in the following. The values for the calculation are shown in Table 13.

$$n_0 = \frac{Z^2 p(1-p)}{e^2} \tag{3}$$

$$n = \frac{n_0}{1+\frac{(n_0-1)}{N}} \tag{4}$$

Based on calculations of the team of Werk150, approximately 60 people will use the MIMB per year. On average, six out of seven MIMBs have the smart lunchbox installed. The MIMB is rented out on a yearly basis. With a life span of five years, this results in a total number of 258 users.

The Z-value describes the confidence and in this case a Z-Value corresponding to about 80 % confidence is used. The aim of the sample is not to reflect the total population as accurately as possible, but to test the product lifecycle and the associated cause-and-effect relationships. Therefore, a lower confidence level can be chosen. The confidence level measures the degree of certainty in terms of how well the sample represents the total population with the selected margin of error. The margin of error refers to the amount of error allowed in the results. Within this experiment, a margin of error of 0.1 is used. This corresponds to 10 % errors allowed in the results. Since the value of the standard deviation is difficult to determine before conducting the actual experiment, the value is set to 0.5. This corresponds to 50 % standard deviation. Using this value ensures that the calculated sample size is large enough to precisely represent the total population within the confidence level and interval.

Table 13: Cochran formula for calculating sample size for smaller populations based on (Cochran, 1954).

Number of MIMB users/year	60	user/year
Life span	5	year
Percentage use of modules	85,71 %	
Total number	258	user
Total population (N)	258	user
Z-value (z)	1,28	
Margin of error (e)	0,1	
Standard deviation (p)	0,5	
Necessary sample size	**36**	**user**

6.2.6 Limitations of the experiment

An essential part of experiment design is to identify and show the limitations of the experiment. The first step is to identify the system to be investigated. This includes determining input variables belonging to the system and input variables lying outside the system. Furthermore, the expected results of the system should be identified (Siebertz et al., 2017, pp. 3-6). To illustrate the system boundaries, a block diagram is developed, which is shown in the following Figure 58.

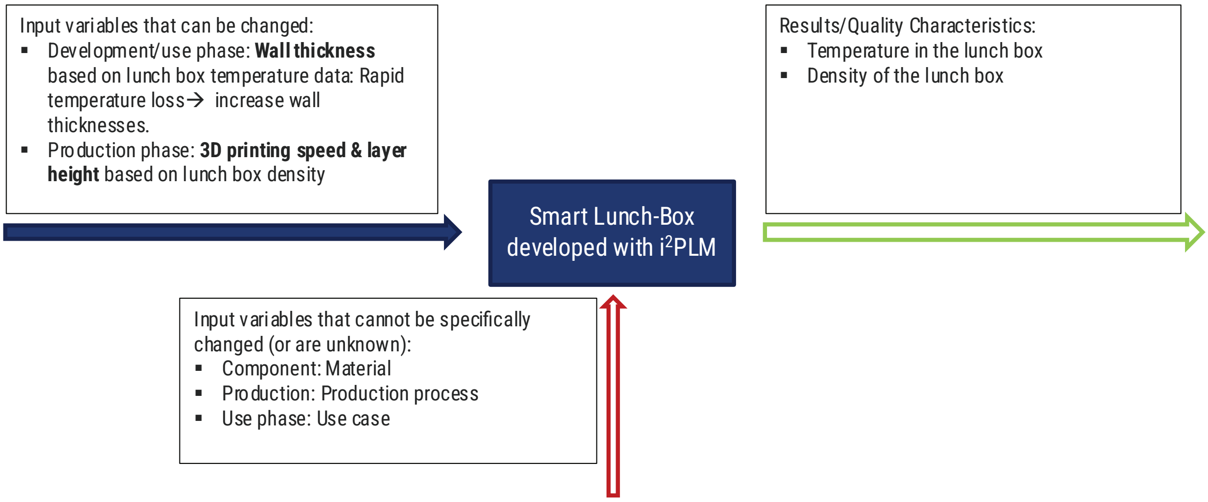


Figure 58: Applied Schematic representation of the system based on (Siebertz et al., 2017, pp. 3-6).

In the context of this validation, the system to be examined is the Smart Lunchbox, which is developed with the i^{2}PLM. The input variables that can be changed are chosen so that the experiment can offer as many inferences as possible, but the procedure is still efficient. In the development phase, the wall thickness of the smart lunchbox can be changed depending on the temperature data generated in the use phase. For example, if a rapid temperature loss is identified during the use phase, the wall thickness can be increased to counteract this. In the production phase, the 3D printing parameters can be adjusted based on the product quality, which in this experiment is the leak-density. In the case where the lunchbox is not leakproof, the 3D printing speed and layer height can be adjusted at conventional printers. The input variables that can be declared as non-changeable are thus outside the system. These are on the one hand the material of the Smart Lunchbox. This is the case because the material MED610 is the only usable 3D printing material that is compatible with food. If there were a wider choice, the variable could be considered changeable. In addition, the change in wall thickness and temperature profile can be correlated, but the change in material cannot be. The production process, with its work steps, also remains unaffected. In order to create similar use cases, this should not be changed. In addition, the characteristics of the use cases are outside the system, since a company has limited possibilities in reality to influence the user. Furthermore, the end-of-life of the product is not taken into account, as the average use phase of a lunchbox five years and therefore too long to be covered by this work (Dallmus & Vollmer, 2016).

As measurable results, the system provides the temperature curve of the smart lunchbox in use phase and the product quality (leak density) in production quality management.

6.3 Results of the validation

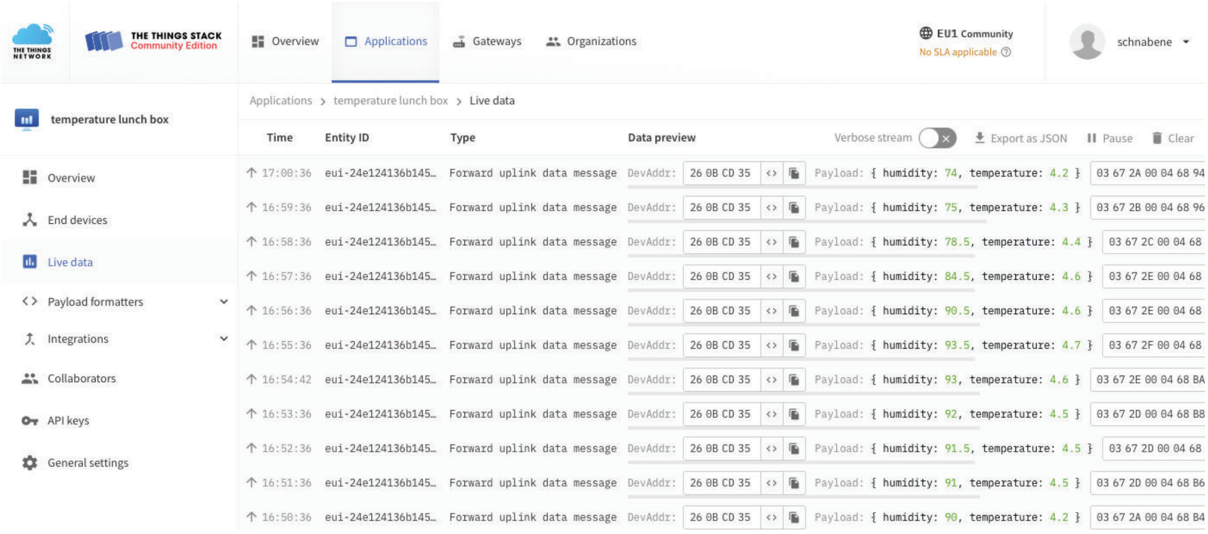
As a first step, *Variant one* of the Smart Lunchbox was produced. This was done in the production environment of Werk150. The following Figure 59 shows the produced *Variant one*.

Figure 59: Smart Lunchbox Variant one.

In the production quality control, the first two production numbers are checked for density and surface condition. It is noticed that number one, which is built in 0°, is leak-proof and number two, which is built in 45°, loses water. It is also noticeable that the surface texture of number two had an irregular surface due to the 45° rotation. These two features are documented in the i^{2}PLM-tool.

In addition, an increased amount of time is noticed in the rework of the 3D print when removing the support material. The reason for this is an overhang in the interior of the box that is difficult to remove. A proposed solution for this would be to adapt the design in *Variant two* so that support material is used only in easily accessible places.

After quality control, the experiment takes place in a real environment in the *verification & validation* process of the use phase. For this purpose, temperature data is recorded in use environments. The data acquisition is done using the Milesight temperature and humidity sensor and The Things LoRaWAN Gateway to store the data. The temperature and humidity curves that are recorded during the experiment are made available via the LoRaWan Gateway in an online cloud. A screenshot from the console of the online application is shown in the following Figure 60. An example of live data with their time stamps and their related humidity and temperature are illustrated.



Time	Entity ID	Type	Data preview		
17:00:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 74, temperature: 4.2 }	03 67 2A 00 04 68 94
16:59:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 75, temperature: 4.3 }	03 67 2B 00 04 68 96
16:58:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 78.5, temperature: 4.4 }	03 67 2C 00 04 68
16:57:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 84.5, temperature: 4.6 }	03 67 2E 00 04 68
16:56:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 90.5, temperature: 4.6 }	03 67 2E 00 04 68
16:55:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 93.5, temperature: 4.7 }	03 67 2F 00 04 68
16:54:42	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 93, temperature: 4.6 }	03 67 2E 00 04 68 BA
16:53:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 92, temperature: 4.5 }	03 67 2D 00 04 68 B8
16:52:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 91.5, temperature: 4.5 }	03 67 2D 00 04 68
16:51:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 91, temperature: 4.5 }	03 67 2D 00 04 68 B6
16:50:36	eui-24e124136b145…	Forward uplink data message	DevAddr: 26 0B CD 35	Payload: { humidity: 90, temperature: 4.2 }	03 67 2A 00 04 68 B4

Figure 60: The Things Network Console.

The data is recorded in JSON format and can be downloaded via the online application. Using a self-developed interface in Python, the data is automatically converted into a ".csv" table format so that it can be processed by the Python-based i^{2}PLM tool in the next step.

The 36-user data are shown in the following diagram in Figure 61. On the horizontal axis the time after removal from the refrigerator is located and on the vertical axis the temperature in °*C*.

The blue temperature curve shows the average of the temperature curves of all 36 user tests. The temperature curve shows that the Smart Lunchbox is not functioning properly in terms of keeping food fresh for an hour. The average temperature one hour after removing from the refrigerator is 19.7 °*C*.

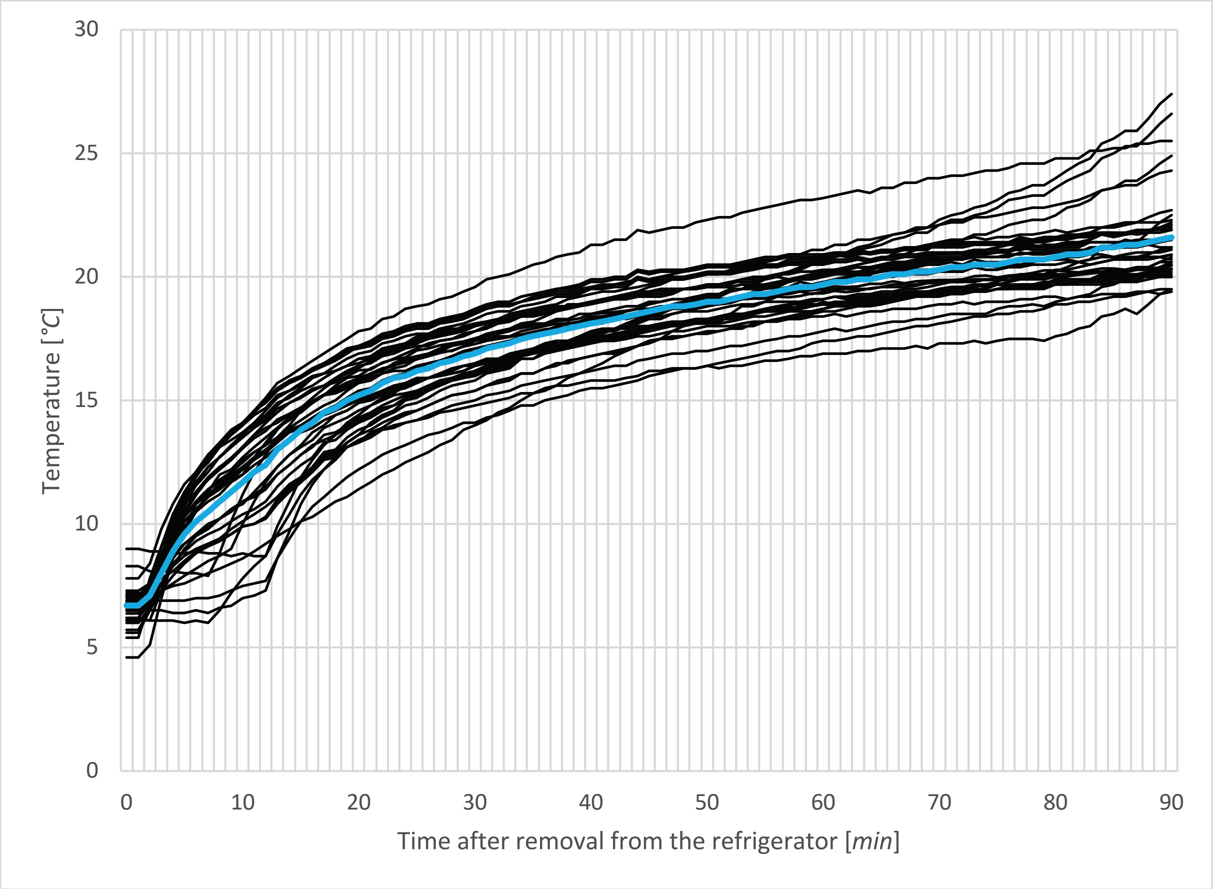
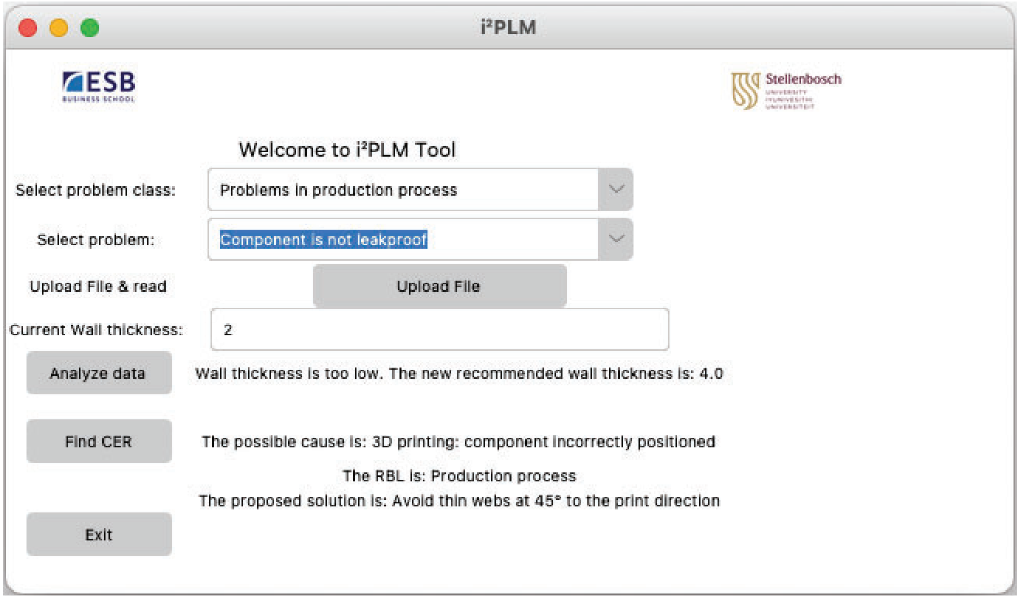


Figure 61: Temperature curve of Smart Lunchbox Variant one.

The data about the quality control in production and the temperature curves can also be analysed automatically in the i²PLM tool. The problem class and the problem of the quality control are inserted, and the temperature curves are transferred. The i²PLM tool identifies component misplacement as a possible cause of leakage in quality control. Furthermore, the tool suggests to increase the wall thickness to four millimetres (mm). The result provided by the i2PLM tool is shown in Figure 62.



Select problem class: Problems in production process

Select problem: Component is not leakproof

Current Wall thickness: 2

Wall thickness is too low. The new recommended wall thickness is: 4.0

The possible cause is: 3D printing: component incorrectly positioned

The RBL is: Production process

The proposed solution is: Avoid thin webs at 45° to the print direction

Figure 62: i²PLM Tool in the validation use case.

The results from the temperature measurement and from the production data serve as the basis for the development of *Variant two*.

Variant two is developed and implemented according to the i²PLM approach. This starts with identifying the user profiles and utilisation in the pre-development phase. In order for the component to result in a new variant, new requirements for the dimensions of the lunchbox are incorporated. Ideas are generated from this, and the first rough drafts are emerged. A prototype is built digitally and thus validated and verified. Then, in the product engineering phase, the user profile and the utilisation are worked out in more detail. The customer's requirements to keep food fresh in the lunchbox for an hour, food compatibility and, that the lunchbox should be waterproof are also taken into account. In addition, the requirement for increased wall thickness from *Variant one* is also considered. To ensure that the product can be decommissioned and remanufactured easily, respective care is taken in the design of the product to ensure that each component is easily replaceable. The product is designed on the basis of these requirements. Since the changes in comparison to *Variant one* are minor, the construction of a prototype is dispensed with. The idea is digitally verified and validated. Afterwards, the product and the production are aligned in the process engineering phase. The designed product is checked against the requirements from production. In addition to the general production requirements, there are requirements that there be no overhangs in the interior of the product and that the product not be printed at a 45° angle. The requirement for overhangs triggers a product design change, which is implemented in the *model solution & embodiment* process. The 3D printing requirement is implemented in the planning of the production environment. The new design is checked again for all original requirements and is then produced in the next step. Within this step, the quality data from the production is recorded again. The results from production quality control are that the *Variant two* is leak-proof, the surface is smoother and the rework effort of the 3D printing is reduced. In the use phase, the product was again tested by 36 users and temperature data recorded. The temperature curves are shown in the following diagram in Figure 63. The average temperature is shown with a blue line and meets the required temperature after one hour with 13.2 *°C*.

Deriving from this, it can be stated that the product in *Variant two* has improved by 6.5 *°C* compared to Variant one. Improvements occurred in the product properties, as well as in the production time and quality.

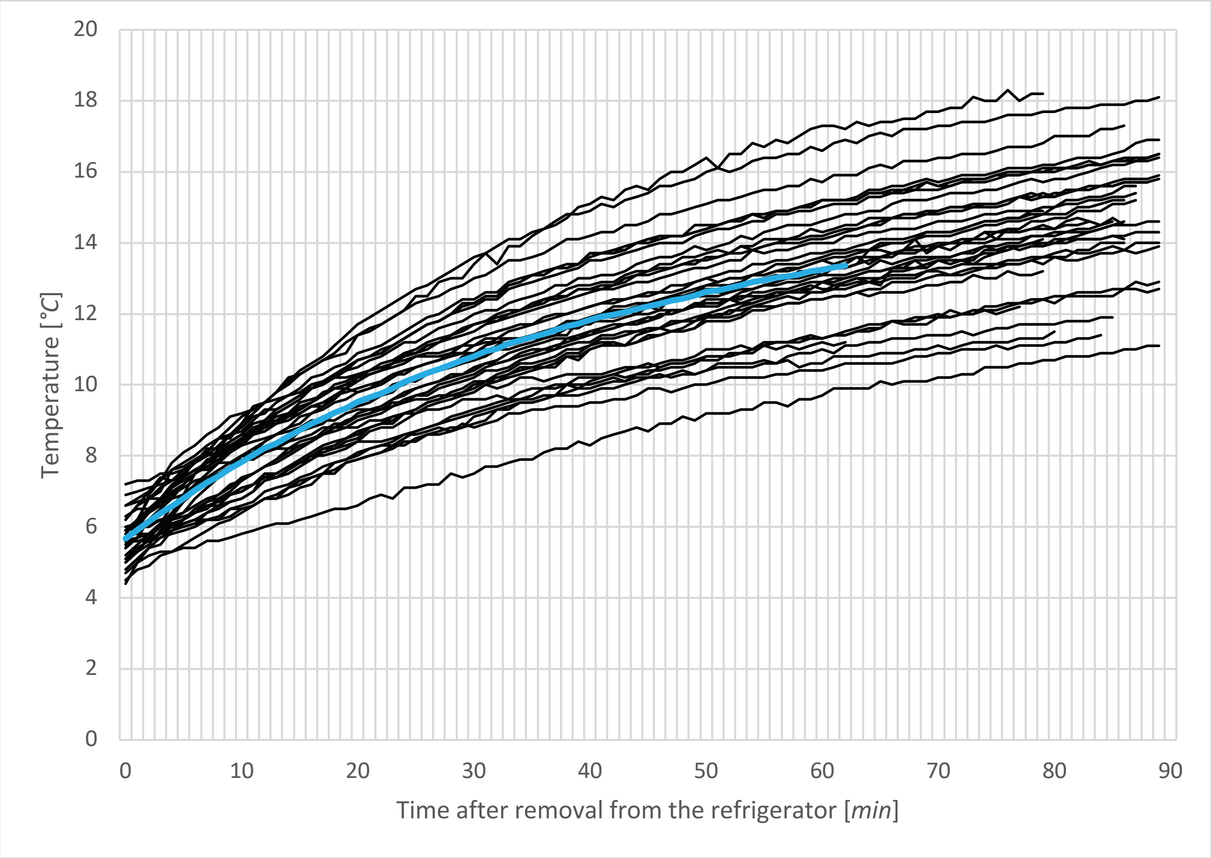


Figure 63: Temperature curve of Smart Lunchbox Variant two.

In addition, the temperature curves of the Smart Lunchbox *Variant two* are also compared with a conventional lunchbox. The conventional lunchbox is comparable due to its dimensions and intended use. The Milesight temperature sensor is integrated into this conventional lunchbox in order to make a comparative measurement of the temperature curve. The same use case is employed. One hour after removal from the refrigerator the temperature of the conventional lunchbox (shown by the black line in Figure 64) is 20 *°C* and the average temperature of the Smart Lunchbox *Variant two* (shown by the dotted line in Figure 64) is 13.2 °*C*. Moreover, this confirmed that the Smart Lunchbox is superior to a conventional lunchbox for this application.

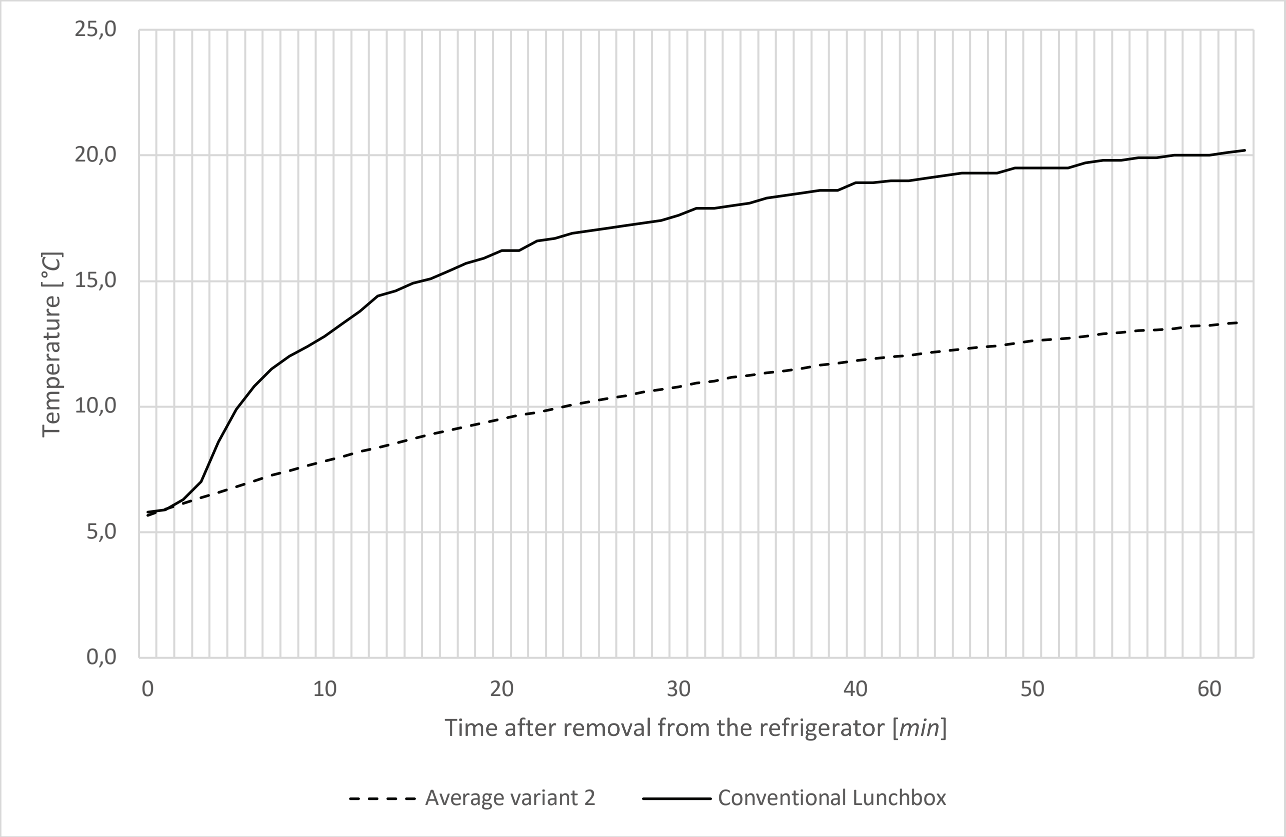


Figure 64: Temperature curve comparison of Smart Lunchbox Variant two and a conventional lunchbox.

6.4 Conclusion

The i²PLM is validated in the context of this work by building a product with two variants of a customisable smart product family. In the case of *Variant one*, data on certain product properties are recorded in the production and use phase. These data serve as the basis for improving the product in the form of *Variant two*. As part of the validation, the integrated and intelligent mechanisms for converting data from other phases into product requirements are checked. As described in the research objective, the data from the smart factory and the smart product are primarily used.

It is detected that the mechanisms of the i²PLM improved the product in *Variant two* compared to *Variant one*. This is measured by an improvement in the quality indicators from production and by improved temperature curves resulting from product characteristics. Additionally, this proved that the correct data is recorded and analysed. In summary, the results confirm the fulfilment of the research objective and hereby a successful implementation of an integrated and intelligent product lifecycle that uses smart factory and smart product data for efficient development of customisable smart product families.

Chapter 7 Summary and conclusion

In this chapter, the research work is summarised and conclusions are drawn. The first Section 7.1 summarises the most important topics from the individual chapters as well as their procedures and results. Then, in the second Section 7.2, the main results and the findings are presented, critically analysed and main conclusions drawn. This also includes the degree of fulfilment of the research objectives and the research answers to the research questions. In the third Section 7.3, the limitations of the work are pointed out and recommendations for future research are given.

7.1 Summary

The thesis is divided into seven chapters, namely: (1) Introduction, (2) Research design and methodology, (3) Current state of research, (4) Identification of cause-and-effect relationships and relevant data types , (5) Creation of the new comprehensive product lifecycle i²PLM, (6) Validation of the product lifecycle i²PLM, (7) Summary and conclusion.

Chapter 1 describes the initial situation and background to the research on product lifecycles in the environment of smart products and smart factories. Based on this, the research problem is elaborated on the basis of the literature. In order to solve this problem, the research questions are posed, and the goals of the research are defined for this thesis.

Chapter 2 outlines the research design and methodology. The research design “design science research” according to Österle is described and adapted to the research work. The scientific-theoretical positioning and the methodology are described in the following for each phase of the research design.

In the third chapter, the current state of science and thus the theoretical state of knowledge is presented. First, the current status in the field of Industry 4.0 is discussed. Part of this is the analysis of smart factories and smart products. Following this, a discussion about intelligent customisable product families is illustrated. After this, the current state of the literature on product lifecycles is described. This description includes the definition of the following range of topics: a product lifecycle and product lifecycle management, the main phases of a product lifecycle, and a differentiation from other business processes. Then product lifecycles and product engineering processes from the literature are described and compared. Generative design is described in the follow-up because it offers a way to automate the design of products based on boundary conditions. Thus, it offers the potential for a more efficient design of products in the product and process engineering phase. The following subchapter describes the theoretical foundations and the procedure for developing cause-and-effect diagrams.

The fourth chapter focuses on the identification of cause-and-effect relationships. Within this chapter, the procedure is first explained and in the next step cause-and-effect relationships are shown with the aid of diagrams. From these cause-and-effect diagrams, the relevant data streams and data types in product lifecycles are derived and presented for each phase.

Chapter 5 develops the novel product lifecycle i²PLM. The procedure is described first. This is followed by the development and simplification of the reference process. This is optimised in the next subchapter. Based on the optimised reference process, the cause-and-effect relationships and the data flows are then incorporated into the reference process. After a further optimisation loop, the i²PLM is generated from this. In the next subchapter, the seven components that make up the i²PLM are described.

Chapter 6 contains the validation of the novel i²PLM. The first step describes how the validation procedure was chosen. Then the experiment including environment, product, number of pieces and limitations is described. Afterwards, the results are presented and conclusions are drawn.

Chapter 7 contains the summary and conclusion. In addition, the contribution to science, limitations and recommendations for further research are described.

7.2 Conclusion and contribution to science

This section presents the main results, the findings for science and the main conclusions. In addition, how the research objectives were achieved is described and an answer is provided to the research questions. Moreover, the contribution to science is outlined.

Table 14: Primary objective.

Primary objective	Creation of an integrated and intelligent product lifecycle that uses smart factory and smart product data for development of customisable smart product families.

The primary objective is the creation of an integrated and intelligent product lifecycle that uses smart factory and smart product data for development of customisable smart product families. It is described in Table 14. The research work provides a newly developed process landscape called i²PLM. The process landscape contains processes of product lifecycles. All six phases of a product lifecycle are represented, namely; (1) pre-development, (2) product engineering, (3) process engineering, (4) production, (5) use and (6) end-of-life.

Based on the literature research, relevant product lifecycles are analysed and combined into a reference process. The elements of the reference processes that are relevant for product lifecycles of smart customisable product families are adopted. In addition, cause-and-effect relationships within a product lifecycle are identified phase by phase. For these cause-and-effect relationships, the relevant data types and data streams are elaborated. From these modules, the i²PLM is created. It is made up of six components, namely; (1) main phases of the product lifecycle, (2) portfolio radar, (3) organisational processes, (4) product lifecycle database, (5) business processes and (6) multi-layer for product portfolio. Based on these components, the main research objective is achieved. Through the organisational processes, the portfolio radar, and the multi-layer representation, the i²PLM is integrated into the entire company context, as it does not only contain one product type, but includes all product types of the company in a process map. This allows processes to be aligned and knowledge to be distributed across product types. The product lifecycle database collects and analyses data from all phases of the product lifecycle. It is firmly integrated into the product lifecycle and into the company. It predominantly uses data from smart products and smart factories. By making the data available at a higher level, intelligent algorithms can draw conclusions from analyses and further optimisations of the products. By using data from all phases of the product lifecycle, requirements can exist fully at the start of development, reducing the number of iteration loops and allowing the product to be developed more efficiently. In addition, the separation of organisational and business processes allows for a higher-level view of the product lifecycle, which means that the phases are considered equally. Based on the portfolio radar and the multi-layer structure, customisable product families can also be developed with the help of this process landscape. Since the planning of sensors and other data acquisition devices is integrated in the pre-development and product engineering, smart products can also be developed.

Table 15: Research question 1 and secondary objective 1.

Research question 1	What are the challenges in product and process engineering for customisable smart products, and which data and information from the smart factory and smart products can reduce these challenges?
Secondary objective 1	Identification of relevant data and information of smart factories and smart products for the product and process engineering of smart customisable product families.

Research question 1 and secondary objective 1 are shown in Table 15. In order to identify the challenges in product engineering and production planning for customisable products and to determine which data can reduce these challenges, a cause-and-effect diagram is created for each phase of the product lifecycle. First, problems and causes of the respective phases are identified based on literature and own knowledge. Then the problems were grouped into problem classes and the causes are assigned to so-called rib-branches. This is graphically represented by the implementation of cause-and-effect diagrams. In this way, for each problem class (corresponds to a phase of the product lifecycle), it is possible to see from which phase the cause originated. For each cause, possible solutions for eliminating the problems are suggested additionally. Data types relevant to the solution are identified for the proposed solutions. The relevance, reliability, availability and data security of the relevant data types are also evaluated. Thus, research question 1 is answered and secondary objective 1 is fulfilled.

Table 16: Research question 2 and secondary objective 2.

Research question 2	What does an approach look like in which smart factory and smart product data are collected and used in product and process engineering?
Secondary objective 2	The development of an approach to use the smart factory and smart product data in a product lifecycle.

Research question 2 and secondary objective 2 are shown in Table 16. To see what an approach could look like in which smart factory and smart product data is collected and used in product development the cause-and-effect relationships and relevant data is used as a basis. The cause-and-effect relationships as well as the proposed solutions and data types are transferred to a self-developed data stream network in this step. In this framework the relevant data streams become visible. The relevance, reliability, availability and data security of the relevant data types are also evaluated. In addition, it is shown whether the data streams are input or output for the respective phases and whether the data is used by the previous, current or for the subsequent generation.

Table 17: Research question 3 and secondary objective 3.

Research question 3	How can the approach for generating, storing and using smart factory and smart product data be integrated into the product lifecycle for the development of customisable smart products?
Secondary objective 3	Integration of the approach into a product lifecycle which has processes that generate, store and use data and information of smart factories and smart products for the development of customisable smart product families.

Research question 3 and secondary objective 3 are shown in Table 17. The detailing of the data streams and the implementation of the approach are executed as part of the i²PLM. Within this process, the product lifecycle database and data streams connecting the processes and database are introduced as a central overarching component. The approach envisages a central database that collects data from all phases of the product lifecycle across all product types. The data streams for this are illustrated in i²PLM and categorised into input and output. In addition, data exchange in the database and analysis of data is supported by tools. An example of a tool called i²PLM-tool is developed in the framework of this thesis. The focus lies on the analysis of data from the production, use and end-of-life phases in the pre-development, product and process engineering phase. The tool can be used to transfer data or manually enter problems that occur within the product lifecycle. The input data is analysed, and solutions are proposed. This allows products to be developed more quickly, qualitatively, and efficiently and to incorporate feedback from previous generations and variants.

Due to the close integration of the product lifecycle database with the business processes, data can be generated for the database on the one hand and data from the database can be used on the other. In addition, the product tends to be designed to work as well as possible with the database. Thus, research question 3 is answered, and the secondary research objective 3 is achieved with the integration of the data streams into the i²PLM and with the product lifecycle database with its example tool.

In Chapter 3.3.2, criteria for evaluating the reference processes were defined. The following is an assessment of how these criteria are met.

Table 18: Reference process evaluation criterion one

Criterion one	The product lifecycle should consider the development of modular product structures or product families.

The reference criteria one, shown in table 18, states that the product lifecycle should consider the development of modular product structures or product families. This criterion is fulfilled by components two and six. Component two provides an overview of the other product types, thus establishing a connection. The multi-layer representation of component six also makes it possible to develop several product types in parallel. However, the development of a modular product structure could be further emphasised and individual processes developed and integrated for this purpose.

Table 19: Reference process evaluation criterion two

Criterion two	The product lifecycle processes should not be designed for products with only one generation but products with multiple generations.

Criterion two is shown in Table 19 and describes that the model should represent several generations.

This is fulfilled by component six, where different product life cycles can be represented by the multi-layer.

Table 20: Reference process evaluation criterion three

Criterion three	The product lifecycle considers the development of a customisable product family.

Criterion three is shown in Table 20 and includes the development of customisable products. The development of customisable products is given by the fact that data from previous variants are anchored in the process by the product lifecycle database (component four) and thus new variants can be developed on the basis of the data in the processes of component five.

Table 21: Reference process evaluation criterion four

Criterion four	The product lifecycle considers the development of smart products. The smart products are equipped with sensors and actuators.

The fourth criterion is shown in Table 21 and asks whether the development of smart products is taken into account. Through the organisational processes (component three) with the management of data, a data strategy is developed at an early stage that defines the requirements for the integration of sensors and actuators into the smart product. These requirements are included in the business processes of component 5. Thus, the development of smart products is actively managed.

Table 22: Reference process evaluation criterion five

Criterion five	The product lifecycle considers process engineering for a smart factory.

Criterion five, which specifies the process engineering of Smart Factory and is shown in Table 22, is represented by the management of data in component three and the development of the production environment in component five. In addition, the data from the Smart Factory flows into the product lifecycle database. Thus, all five criteria for evaluating the reference processes are fulfilled by various components of the i^{2}PLM. For this reason, the i^{2}PLM is suitable for the use case.

The i^{2}PLM is applied in the validation chapter of the master thesis within the scope of an experiment. The aim of the validation is to check whether the i^{2}PLM is applicable and fulfils the requirements. The experiment is carried out at the research facility of Reutlingen University on a smart lunchbox with two variants.

By adapting the development of a product based on different data, the approach and the data streams are checked to see whether this would improve the product. A component of this is to check whether the correct data types are recorded and analysed and whether this results in an improvement of the product. Thus, it can be stated that the validation confirms the applicability and correctness of the data streams for this use case, but not whether the i^{2}PLM is generally applicable. However, it can also be seen that the result strongly depends on the definition of the functions, which are based on cause-and-effect relationships.

7.3 Research limitations and recommendations for further research

First, the limitations of the i²PLM are presented, followed by recommendations for further research.

The aim of the i²PLM is to make the development of smart customisable product families more efficient and thus to make mass customisation feasible in product lifecycle management. For this purpose, cause-and-effect diagrams are created at the outset. The creation of the cause-and-effect diagrams is done manually within the scope of this work and is partly based on personal experience in product lifecycles. This conventional approach describes more a qualitative approach than a quantitative one. As little data from other companies is freely available, it is not yet possible to automatically create cause-and-effect relationships. In addition, the i²PLM is strongly dependent on cause-and-effect relationships.

Furthermore, within the i²PLM framework it is not described how the i²PLM can be integrated into a company and there is only limited literature about the introduction of new product lifecycles. Since the cause-and-effect relationships in each company and in each sector can be individual, different characteristics can arise. Also, cause-and-effect relationships can change over time. A procedure for adjusting and updating the i²PLM is not described.

As a suggestion for further optimisation of the model, the cause-and-effect relationships can be created automatically based on data. This reduces the manual effort and objectifies the relationships through automated data analysis. In research, however, it should be investigated whether automated generation delivers the desired results. Another advantage of automated data analysis is that not only the relationships that cause problems are examined, but also all other relationships between variables. This gives a broader view of the situation in a company and important connections between variables can be detected.

Further research is needed to analyse a broader set of possible cause-and-effect relationships and apply them to the i²PLM. Given the large number of cause-and-effect relationships, criteria can also be established that describe the situations in which they apply. In addition, further research should be conducted on how new cause-and-effect relationships can be efficiently integrated into the i²PLM tools and how the existing PLM tools can be combined with the i²PLM.

Until now, there has been only limited research on necessary steps for introducing a new product lifecycle in a company, as well as for introducing new product platforms. Further research on a company's adaptation strategy to the i²PLM is recommended to make it easily applicable to users. With good applicability, the i²PLM is used more widely and can be further optimised through the multitude of use cases. In further research regarding the product lifecycle database, standards and norms should be adhered to or adapted in the implementation.

References

Ahmed, M. B., Majeed, F., Sanin, C., & Szczerbicki, E. (2020). Enhancing product manufacturing through smart virtual product development (SVPD) for Industry 4.0. *Cybernetics and Systems*, *51*(2), 246-257.

Albers, A., & Braun, A. (2011). A generalised framework to compass and to support complex product engineering processes. *International Journal of Product Development*, *15*(1-3), 6-25.

Albers, A., Burkardt, N., Meboldt, M., & Saak, M. (2005). SPALTEN problem solving methodology in the product development. DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08. 2005,

Albers, A., Reiss, N., Bursac, N., & Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP*, *50*, 100-105. https://doi.org/10.1016/j.procir.2016.04.168

Albers, A., Reiß, N., Bursac, N., Urbanec, J., & Ludcke, R. (2014). Situation-appropriate method selection in product development process–empirical study of method application. *DS 81: Proceedings of NordDesign 2014, Espoo, Finland 27-29th August 2014*.

Albert, A., & Mirko, M. (2007). IPEMM-integrated product development process management model, based on systems engineering and systematic problem solving. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

Allmann, C. (2007). Automobile Vorentwicklung, Anforderungsmanagement auf der grünen Wiese. *GI Softwaretechnik-Trends*, *27*(1).

Autodesk. (2022). *Generative Design*. Autodesk Inc. Retrieved 08.09.2022 from

Azuma, R. T. (1997). A survey of augmented reality. *Presence: teleoperators & virtual environments*, *6*(4), 355-385.

Bag, S., Yadav, G., Dhamija, P., & Kataria, K. K. (2021). Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study. *Journal of Cleaner Production*, *281*, 125233. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.125233

Bauer, W., Bender, M., Braun, M., Rally, P., & Scholtz, O. (2016). Leichtbauroboter in der manuellen Montage–einfach einfach anfangen. *IRB Mediendienstleistungen, Stuttgart*.

Bauernhansl, T. (2017). Die vierte industrielle Revolution–Der Weg in ein wertschaffendes Produktionsparadigma. In *Handbuch Industrie 4.0 Bd. 4* (pp. 1-31). Springer.

Beckschulte, S., Kiesel, R., & Schmitt, R. H. (2021). Manuelle Fehleraufnahme bei Mass Customization. *Entwicklung eines Prozessmodells zur manuellen Fehlerdatenaufnahme in der Montage am Beispiel eines Nutzfahrzeugherstellers*, *116*(4), 188-192. https://doi.org/doi:10.1515/zwf-2021-0038

Benner-Wickner, M., Kneuper, R., & Schlömer, I. (2020). *Leitfaden für die Nutzung von Design Science Research in Abschlussarbeiten*.

Berekoven, L., Eckert, W., & Ellenrieder, P. (1989). *Marktforschung*. Springer.

Bergera, C., Heesa, A., Braunreuthera, S., & Reinharta, G. (2015). Characterization of cyber-physical sensor systems Proc. 48th CIRP Conf. on Manufacturing Systems (Naples).

Biffl, S., Lüder, A., & Gerhard, D. (2017). *Multi-Disciplinary Engineering for Cyber-Physical Production Systems*. https://doi.org/10.1007/978-3-319-56345-9

Biral, A., Centenaro, M., Zanella, A., Vangelista, L., & Zorzi, M. (2015). The challenges of M2M massive access in wireless cellular networks. *Digital Communications and Networks*, *1*(1), 1-19.

Bosch-Sijtsema, P., & Bosch, J. (2015). User involvement throughout the innovation process in high-tech industries. *Journal of Product Innovation Management*, *32*(5), 793-807.

Browning, T. R., Fricke, E., & Negele, H. (2006). Key concepts in modeling product development processes. *Systems Engineering*, *9*(2), 104-128.

Bundesamt, S. (2016). *Zeitaufwand für den Weg zum Arbeitsplatz*. Retrieved 12.07.2022 from https://www.destatis.de/DE/Themen/Arbeit/Arbeitsmarkt/Qualitaet-Arbeit/Dimension-3/zeitaufwand-weg-arbeit.html

Cabrera-Rojas, K., Chavez-Gallardo, A., & Cabanillas-Carbonell, M. (2023). Business Intelligence to Improve Decision Making in the Production Process. Proceedings of Seventh International Congress on Information and Communication Technology,

Cochran, W. G. (1954). Some Methods for Strengthening the Common χ 2 Tests. *Biometrics*, *10*(4), 417. https://doi.org/10.2307/3001616

Costa, M. A. B., & Toledo, J. C. d. (2016). Analisis of predevelopment models and activities: a systematic bibliografic review. *Gestão & Produção*, *23*, 704-717.

Dafflon, B., Moalla, N., & Ouzrout, Y. (2021). The challenges, approaches, and used techniques of CPS for manufacturing in Industry 4.0: a literature review. *The International Journal of Advanced Manufacturing Technology*, *113*(7), 2395-2412. https://doi.org/10.1007/s00170-020-06572-4

Dallmus, A., & Vollmer, S. (2016). *Butterbrotpapier oder Brotbox - was ist besser?* Bayrischer Rundfunk. Retrieved 26.10.2022 from https://www.br.de/radio/bayern1/inhalt/experten-tipps/umweltkommissar/brotzeit-brotbox-butterbrotpapier-verpackung-umwelt-100.html

Ding, T., Yan, G., Zhou, Z., & Lei, Y. (2022). A novel manufacturing service model transformation method based on product lifecycle. *Peer-to-Peer Networking and Applications*, *15*(3), 1638-1652.

Douma, E., Belderok, A., & Roelofsma, M. (2019). *Roland Berger Focus – A modular future* (Roland Berger Focus, Issue. R. Berger. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi47rT5j5n6AhWhhP0HHVaWB4IQFnoECBAQAQ&url=https%3A%2F%2Fwww.rolandberger.co

m%2Fpublications%2Fpublication_pdf%2Froland_berger_modularization_1.pdf&usg=AOvVaw019DAgg17D6gCD346K1Zqx

Duchi, A., Pourabdollahian, G., Sili, D., Cioffi, M., Taisch, M., & Schönsleben, P. (2014). Motivations and Challenges for Engineer-to-Order Companies Moving toward Mass Customization. In B. Grabot, B. Vallespir, S. Gomes, A. Bouras, & D. Kiritsis, *Advances in Production Management Systems. Innovative and Knowledge-Based Production Management in a Global-Local World* Berlin, Heidelberg.

Duda, J., Oleszek, S., & Santarek, K. (2022). Product Lifecycle Management (PLM) in the Context of Industry 4.0. International Scientific-Technical Conference MANUFACTURING,

Feldhusen, J., & Grote, K.-H. (2013a). Der Produktentstehungsprozess (PEP). In *Pahl/Beitz Konstruktionslehre* (pp. 11-24). Springer.

Feldhusen, J., & Grote, K.-H. (2013b). *Pahl/Beitz Konstruktionslehre*. Springer.

Fenz, S., & Ekelhart, A. (2010). Verification, validation, and evaluation in information security risk management. *IEEE Security & Privacy*, *9*(2), 58-65.

Ferencz, K., Domokos, J., & KovÁCs, L. (2021, 19-21 May 2021). Review of Industry 4.0 Security Challenges. 2021 IEEE 15th International Symposium on Applied Computational Intelligence and Informatics (SACI),

Gauss, L., Lacerda, D. P., & Cauchick Miguel, P. A. (2021). Module-based product family design: systematic literature review and meta-synthesis. *Journal of Intelligent Manufacturing*, *32*(1), 265-312. https://doi.org/10.1007/s10845-020-01572-3

Gernhardt, B., Vogel, T., & Hemmje, M. (2018). Knowledge-based production planning for industry 4.0. In *Semantic Applications* (pp. 181-202). Springer.

Gilmore, J. H., & Pine, B. J. (1997). The four faces of mass customization. *Harvard business review*, *75*(1), 91-102.

Groombridge, D. (2022). *Top Strategic Technology Trends for 2022 - 12 Trends Shaping the Future of Digital Business*. G. Inc.

Günther, R., Beckschulte, S., Wende, M., & Schmitt, R. H. (2022). Wertschöpfungskettenübergreifendes Fehlermanagement. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *117*(4), 187-191.

Hajda, J., Jakuszewski, R., & Ogonowski, S. (2021). Security Challenges in Industry 4.0 PLC Systems. *Applied Sciences*, *11*(21), 9785. https://www.mdpi.com/2076-3417/11/21/9785

Hankel, M., & Rexroth, B. (2015). Das Referenzarchitekturmodell Industrie 4.0 (RAMI 4.0). *Zentralverband Elektrotechnik-und Elektronikindustrie e. V. URL: https://www. zvei. org/fileadmin/user_upload/Presse_ und_Medien/Publikationen/2015/april/Das_Referenzarch itekturmodell_Industrie_4. 0__RAMI_4. 0_/Faktenblatt-Industrie4_0-RAMI-4_0. pdf (besucht am 01. 11. 2019)*.

Haußmann, C. (2012). Erstellung eines Konzepts für ETL-Prozesse zur Befüllung von produktorientierten Datawarehouses. WSBI, Herrmann, C. (2010). *Ganzheitliches Life Cycle Management: Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen*. Springer-Verlag.

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS quarterly*, 75-105.

Hillnhagen, S., Green, T., Maier, J. T., Mütze, A., & Schmidt, M. (2021). Wirkzusammenhänge innerhalb der Produktionsplanung und -steuerung. *Ein Ansatz zur generischen Modellierung der Zusammenhänge zwischen Aufgaben der PPS und produktionslogistischen Zielgrößen*, *116*(12), 889-894. https://doi.org/doi:10.1515/zwf-2021-0221

Hu, S. J. (2013). Evolving paradigms of manufacturing: From mass production to mass customization and personalization. *Procedia CIRP*, *7*, 3-8.

Huang, G. Q., Li, L., Lau, T., & Chen, X. (2007). A generic and extensible information infrastructure framework for mass-customizing platform products. *International Journal of Computer Integrated Manufacturing*, *20*(2-3), 292-306.

Irfana Parveen, C., Anjali, O., & Sunder, R. (2023). Internet of Things: A Review on Its Applications. *Information and Communication Technology for Competitive Strategies (ICTCS 2021)*, 123-134.

Jagusch, K., Sender, J., & Flügge, W. (2019). Transparency in the design-accompanying production on shipyards. *Procedia CIRP*, *81*, 791-796.

Jagusch, K., Sender, J., & Flügge, W. (2020). Databased product adjustments during manufacturing based on agile production and digital representation in shipbuilding prefabrication. *Procedia CIRP*, *93*, 789-794.

Jänsch, J., & Birkhofer, H. (2006). The development of the guideline VDI 2221-the change of direction. DS 36: Proceedings DESIGN 2006, the 9th International Design Conference, Dubrovnik, Croatia,

Jericho, D., Jagusch, K., Sender, J., & Flügge, W. (2020). Herausforderungen in der durchgängigen Produktionsplanung bei ETO-Produkten. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *115*(12), 890-893. https://doi.org/doi:10.3139/104.112472

Jiang, R. (2015). Engineering Activities in Product Life Cycle. In R. Jiang (Ed.), *Introduction to Quality and Reliability Engineering* (pp. 11-25). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-47215-6_2

Johansson, E., Bergdahl, D., Bosch, J., & Olsson, H. H. (2015, Jun 16-17). Quantitative Requirements Prioritization from a Pre-development Perspective.*Communications in Computer and Information Science* [Software process improvement and capability determination, spice 2015]. 15th International Conference on Software Process Improvement and Capability dEtermination (SPICE), Gothenburg, SWEDEN.

Karadayi-Usta, S. (2020). An Interpretive Structural Analysis for Industry 4.0 Adoption Challenges. *IEEE Transactions on Engineering Management*, *67*(3), 973-978. https://doi.org/10.1109/TEM.2018.2890443

Kent, M. (2006). *Oxford dictionary of sports science and medicine*. OUP Oxford.

Khorasani, M., Loy, J., Ghasemi, A. H., Sharabian, E., Leary, M., Mirafzal, H., Cochrane, P., Rolfe, B., & Gibson, I. (2022). A review of Industry 4.0 and additive manufacturing synergy. *Rapid Prototyping Journal*, *28*(8), 1462-1475. https://doi.org/10.1108/RPJ-08-2021-0194

Khurana, A., & Rosenthal, S. R. (1998). Towards holistic "front ends" in new product development. *Journal of Product Innovation Management: An international publication of the product development & management association*, *15*(1), 57-74.

Klanitz, T. (2022). *Poka Yoke*. REFA AG. Retrieved 31.10.2022 from https://refa.de/service/refa-lexikon/poka-yoke

Kleiner, S., & Kramer, C. (2013). Model based design with systems engineering based on RFLP using V6. In *Smart Product Engineering* (pp. 93-102). Springer.

Klostermeier, R., Haag, S., & Benlian, A. (2020). Geschäftsmodelle digitaler Zwillinge. *Geschäftsmodelle digitaler Zwillinge: HMD Best Paper Award 2018*, 1-35.

Kohlbeck, E., Baimler, B. C., Beuren, F. H., Fagundes, A. B., & Pereira, D. (2020). Praticidade e sustentabilidade no processo metodológico de pré-desenvolvimento de produtos. *DAPesquisa*, *15*(0), 01-24. https://doi.org/10.5965/18083129152020e0004

Kohlbeck, E., Melo, A., Fagundes, A. B., Pereira, D., Beuren, F. H., & Ueno, O. K. (2021). PRE-DEVELOPMENT OF PRODUCTS: METHODOLOGY APPLIED IN A PROPOSAL ORIENTED TO THE SUSTAINABLE DEVELOPMENT GOALS. *Journal on Innovation and Sustainability RISUS*, *12*(1), 116-134.

Krause, D., & Gebhardt, N. (2018). *Methodische Entwicklung modularer Produktfamilien: Hohe Produktvielfalt beherrschbar entwickeln*. Springer-Verlag.

Krause, D., Vietor, T., Inkermann, D., Hanna, M., Richter, T., & Wortmann, N. (2021). Produktarchitektur. In B. Bender & K. Gericke (Eds.), *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung* (pp. 335-393). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-57303-7_12

Krish, S. (2011). A practical generative design method. *Computer-Aided Design*, *43*(1), 88-100. https://doi.org/https://doi.org/10.1016/j.cad.2010.09.009

Kull, H. (2015). *Mass customization: Opportunities, methods, and challenges for manufacturers*. https://doi.org/10.1007/978-1-4842-1007-9

Kunath, M., & Winkler, H. (2018). Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process. *Procedia CIRP*, *72*, 225-231. https://doi.org/https://doi.org/10.1016/j.procir.2018.03.192

Kunz, S. F., Carolin; Weiß, Julian; Genswein, Max; Kemmner, Fabian; Olivieri, Aylin; Emirzeoglu, Ismet. (2022). *Entwicklung eines neuen Produktes für das Werk150 unter Berücksichtigung der Aspekte der Circular Economy* [Project Report, Reutlingen-University].

Lange, F. (2021). *Prozessgerechte Topologieoptimierung für die Additive Fertigung*. Springer.

Lapusan, C., Lapusan, M., Brisan, C., & Chiroiu, V. (2019). Aspects relating to development of modular design in mass customization production.

Lee, I., & Lee, K. (2015). The Internet of Things (IoT): Applications, investments, and challenges for enterprises. *Business Horizons*, *58*. https://doi.org/10.1016/j.bushor.2015.03.008

Leitão, P., Pires, F., Karnouskos, S., & Colombo, A. W. (2020). Quo vadis industry 4.0? Position, trends, and challenges. *IEEE Open Journal of the Industrial Electronics Society*, *1*, 298-310.

Leloglu, E. (2017). A Review of Security Concerns in Internet of Things. *Journal of Computer and Communications*, *5*, 121-136.

Leopold, T. A., Ratcheva, V., & Zahidi, S. (2018). The future of jobs report. Cologny/Genf: World Economic Forum,

Li, H., & Lachmayer, R. (2018). Generative design approach for modeling creative designs. IOP Conference Series: Materials Science and Engineering,

Lieberman, M. B., & Montgomery, D. B. (1988). First‐mover advantages. *Strategic management journal*, *9*(S1), 41-58.

Liu, N., Chow, P.-S., & Zhao, H. (2020). Challenges and critical successful factors for apparel mass customization operations: recent development and case study. *Annals of Operations Research*, *291*(1), 531-563. https://doi.org/10.1007/s10479-019-03149-7

Lu, Y. (2021). The Current Status and Developing Trends of Industry 4.0: a Review [Review; Early Access]. *Information Systems Frontiers*, 20. https://doi.org/10.1007/s10796-021-10221-w

MacDuffie, J. (1997). The Road to "Root Cause": Shop-Floor Problem-Solving at Three Auto Assembly Plants. *Management Science*, *43*, 479-502. https://doi.org/10.1287/mnsc.43.4.479

Macke, N., Rulhoff, S., & Stjepandic, J. (2012). Reference planning processes for series production. In *Enabling Manufacturing Competitiveness and Economic Sustainability* (pp. 539-543). Springer.

Mandel, C., Stürmlinger, T., Yue, C., Behrendt, M., & Albers, A. (2020, 24 Aug.-20 Sept. 2020). Model-Based Systems Engineering Approaches for the integrated development of product and production systems in the context of Industry 4.0. 2020 IEEE International Systems Conference (SysCon),

Meyer, M. H., & Lehnerd, A. P. (1997). *The power of product platforms*. Simon and Schuster.

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321-1329.

Moeckel, A., & Forcellini, F. A. (2007, 2007). Collaborative product pre-development: an architecture proposal. [Complex systems concurrent engineering: Collaboration, technology innovation and sustainability]. 14th International Conference on Concurrent Engineering, Sao Paulo, BRAZIL.

Monostori, L. (2014). Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. *Procedia CIRP*, *17*, 9–13. https://doi.org/10.1016/j.procir.2014.03.115

Müller-Stewens, B., & Möller, K. (2017). Performance in new product development: a comprehensive framework, current trends, and research directions. *Journal of Management Control*, *28*(2), 157-201. https://doi.org/10.1007/s00187-016-0243-4

Mund, K., Pieterse, K., & Cameron, S. (2015). Lean product engineering in the South African automotive industry. *Journal of Manufacturing Technology Management*, *26*(5), 703-724. https://doi.org/10.1108/JMTM-05-2013-0062

Niemann, J., & Pisla, A. (2021). *Life-Cycle Management of Machines and Mechanisms*. Springer.

Nourbakhsh, M., Morris, N., Bergin, M., Iorio, F., & Grandi, D. (2016). *Embedded Sensors and Feedback Loops for Iterative Improvement in Design Synthesis for Additive Manufacturing*. https://doi.org/10.1115/DETC2016-59627

Oesterle, H., Becker, J., Hess, T., Karagiannis, D., Krcmar, H., Loos, P., Mertens, P., Oberweis, A., & Sinz, E. (2010). Memorandum zur gestaltungsorientierten Wirtschaftsinformatik. *http://www.alexandria.unisg.ch/Publikationen/71074*, *62*. https://doi.org/10.1007/BF03372838

Otto, K., Hölttä-Otto, K., Simpson, T., Krause, D., Ripperda, S., & Moon, S. (2016). Global Views on Modular Design Research: Linking Alternative Methods to Support Modular Product Family Structure Design. *Journal of Mechanical Design*, *138*. https://doi.org/10.1115/1.4033654

Oztemel, E., & Gursev, S. (2020a). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*. https://doi.org/10.1007/s10845-018-1433-8

Oztemel, E., & Gursev, S. (2020b). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, *31*(1), 127-182. https://doi.org/10.1007/s10845-018-1433-8

Pan, X.-W., Zhu, X.-Y., Ji, Y.-J., Yang, Y., & Wu, Y.-M. (2014). An information integration modelling architecture for product family life cycle in mass customisation. *International Journal of Computer Integrated Manufacturing*, *27*(9), 869-886. https://doi.org/10.1080/0951192X.2013.869833

Pessoa, M., & Jauregui-Becker, J. (2020). Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development. *Research in Engineering Design*, *31*, 1-21. https://doi.org/10.1007/s00163-020-00330-z

Pine, B. J., II. (1993a). *Mass Customization: The New Frontier in Business Competition*. Harvard Business School Press.

Popper, K. R. (1989). Logik der Forschung.

ProSTEP. (2010). *Produktionsplanungsprozesse - Ein Referenzprozess verbindet Konstruktion und Produktion*.

Querbes, A., & Frenken, K. (2017). Evolving user needs and late-mover advantage. *Strategic organization*, *15*(1), 67-90.

Raff, S., Wentzel, D., & Obwegeser, N. (2020). Smart products: conceptual review, synthesis, and research directions. *Journal of Product Innovation Management*, *37*(5), 379-404.

Rauch, E., Rojas, R., Dallasega, P., & Matt, D. T. (2018). Smart shopfloor management. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, *113*(1-2), 17-21.

Reutlingen-University. (2022). *Werk 150*. Hochschule Reutlingen. Retrieved 28.08.2022 from

Richter, A., Sadek, T., & Steven, M. (2010). Flexibility in industrial product-service systems and use-oriented business models. *CIRP Journal of Manufacturing Science and Technology*, *3*(2), 128-134. https://doi.org/https://doi.org/10.1016/j.cirpj.2010.06.003

Ropohl, G. (1975). Einleitung in die Systemtechnik. *Systemtechnik–Grundlagen und Anwendung, München Wien, Carl Hanser Verlag*, 1-77.

Roto, V., Lee, J.-J., Mattelmäki, T., & Zimmerman, J. (2018). Experience Design meets Service Design: Method Clash or Marriage? Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems,

Shao, W. P., Hao, Y. P., & Zeng, P. F. (2012). Study on product family architecture dynamic evolution based on product instances. Advanced Materials Research,

Siebertz, K., Hochkirchen, T., & van Bebber, D. (2017). *Statistische Versuchsplanung* (2. Auflage ed.). Springer.

Sikhwal, R. K., & Childs, P. R. N. (2017, 10-13 Dec. 2017). Product design for mass individualisation for industrial application. 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),

Stark, J. (2011). Product Lifecycle Management. In J. Stark (Ed.), *Product Lifecycle Management: 21st Century Paradigm for Product Realisation* (pp. 1-16). Springer London. https://doi.org/10.1007/978-0-85729-546-0_1

Stark, J. (2022). Product Lifecycle Management (PLM). In *Product Lifecycle Management (Volume 1)* (pp. 1-32). Springer.

Stark, R. (2017). Smarte Fabrik 4.0–Digitaler Zwilling. *Themenblatt Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK*, 1-3.

Stark, R., Beier, G., Rothenburg, U., & Woll, R. (2012). *Modellbasiertes systems engineering: Durchgängige Entwicklung mit erlebbaren Prototypen*. PLMportal.

Steinhardt, G. (2010). Extending product life cycle stages. In *The Product Manager's Toolkit* (pp. 69-76). Springer.

Stempfle, J. (2011). Overcoming Organizational Fixation: Creating and Sustaining an Innovation Culture. *The Journal of Creative Behavior*, *45*. https://doi.org/10.1002/j.2162-6057.2011.tb01091.x

Strozzi, F., Colicchia, C., Creazza, A., & Noè, C. (2017). Literature review on the 'Smart Factory' concept using bibliometric tools [Article]. *International Journal of Production Research*, *55*(22), 6572-6591. https://doi.org/10.1080/00207543.2017.1326643

Suarez, F., & Lanzolla, G. (2005). The half-truth of first-mover advantage. *Harvard business review*.

Thomassen, M. K., & Alfnes, E. (2017). Mass Customization Challenges of Engineer-to-Order Manufacturing. In J. Bellemare, S. Carrier, K. Nielsen, & F. T. Piller, *Managing Complexity* Cham.

Tomiyama, T., Lutters, E., Stark, R., & Abramovici, M. (2019). Development capabilities for smart products. *CIRP Annals*, *68*(2), 727-750.

Töpfer, A. (2012). *Erfolgreich Forschen: Ein Leitfaden für Bachelor-, Master-Studierende und Doktoranden*. Springer-Verlag.

Trautmann, L. (2021). Product customization and generative design. *Multidiszciplináris tudományok*, *11*(4), 87-95.

Trotta, D., & Garengo, P. (2018, 7-9 March 2018). Industry 4.0 key research topics: A bibliometric review. 2018 7th International Conference on Industrial Technology and Management (ICITM),

Vahid, S., & Wang, S. (2017). *USING POINT CLOUD TECHNOLOGY FOR PROCESS SIMULATION IN THE CONTEXT OF DIGITAL FACTORY BASED ON A SYSTEMS ENGINEERING INTEGRATED APPROACH*.

VDI. (1993). VDI 2221: Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte. In: Verein Deutscher Ingenieure Std.

Wabia, C., Wabia, & Reibold. (2020). *The Cultural Influence on Mass Customization*. Springer.

Wang, Y., Ma, H.-S., Yang, J.-H., & Wang, K.-S. (2017). Industry 4.0: a way from mass customization to mass personalization production. *Advances in manufacturing*, *5*. https://doi.org/10.1007/s40436-017-0204-7

Wei, J., Courbis, A.-L., Lambolais, T., Xu, B., Bernard, P. L., & Dray, G. (2022). Towards a Data-Driven Requirements Engineering Approach: Automatic Analysis of User Reviews. *arXiv preprint arXiv:2206.14669*.

Wittmann, S., & Stockinger, A. (2006). Volumenvisualisierung von abweichungsbehafteter Geometrie. DFX 2006: Proceedings of the 17th Symposium on Design for X, Neukirchen/Erlangen, Germany, 12.-13.10. 2006,

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

Wong, C. Y., McFarlane, D., Zaharudin, A., & Agarwal, V. (2002). *The intelligent product driven supply chain* (Vol. 4). https://doi.org/10.1109/ICSMC.2002.1173319

Xu, Z. G., & Dang, Y. Z. (2020). Automated digital cause-and-effect diagrams to assist causal analysis in problem-solving: a data-driven approach [Article]. *International Journal of Production Research*, *58*(17), 5359-5379. https://doi.org/10.1080/00207543.2020.1727043

Yassine, A., & Souweid, S. (2021). Time-to-Market and Product Performance Tradeoff Revisited. *IEEE Transactions on Engineering Management*.

Yassine, A., & Souweid, S. (2021). Time-to-Market and Product Performance Tradeoff Revisited. *IEEE Transactions on Engineering Management*, 1-16. https://doi.org/10.1109/TEM.2021.3081987

Zhang, Q., Lu, X., Peng, Z., & Ren, M. (2019). Perspective: a review of lifecycle management research on complex products in smart-connected environments. *International Journal of Production Research*, *57*(21), 6758-6779. https://doi.org/10.1080/00207543.2019.1587186

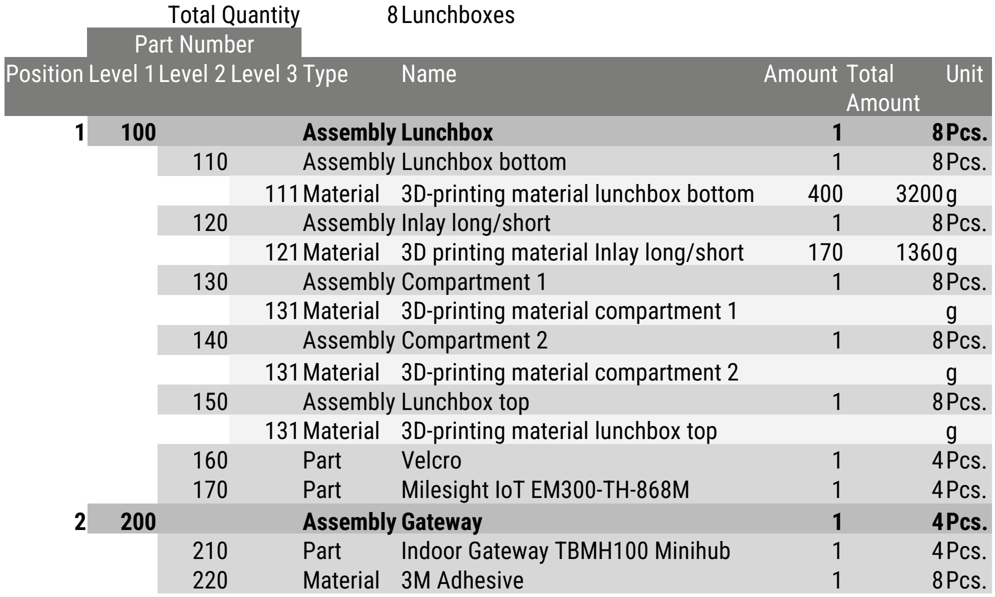
Zhang, Y. F., Ren, S., Liu, Y., Sakao, T., & Huisingh, D. (2017). A framework for Big Data driven product lifecycle management [Article]. *Journal of Cleaner Production*, *159*, 229-240. https://doi.org/10.1016/j.jclepro.2017.04.172

Appendix A

In the appendix the bill of material of the smart lunchbox is shown.

A.1 Bill of material of the Smart Lunchbox

Table 23: Bill of material of the Smart Lunchbox



Total Quantity 8 Lunchboxes

	Part Number							
Position	Level 1	Level 2	Level 3	Type	Name	Amount	Total Amount	Unit
1	**100**			**Assembly**	**Lunchbox**	**1**	**8**	**Pcs.**
		110		Assembly	Lunchbox bottom	1	8	Pcs.
			111	Material	3D-printing material lunchbox bottom	400	3200	g
		120		Assembly	Inlay long/short	1	8	Pcs.
			121	Material	3D printing material Inlay long/short	170	1360	g
		130		Assembly	Compartment 1	1	8	Pcs.
			131	Material	3D-printing material compartment 1			g
		140		Assembly	Compartment 2	1	8	Pcs.
			131	Material	3D-printing material compartment 2			g
		150		Assembly	Lunchbox top	1	8	Pcs.
			131	Material	3D-printing material lunchbox top			g
		160		Part	Velcro	1	4	Pcs.
		170		Part	Milesight IoT EM300-TH-868M	1	4	Pcs.
2	**200**			**Assembly**	**Gateway**	**1**	**4**	**Pcs.**
		210		Part	Indoor Gateway TBMH100 Minihub	1	4	Pcs.
		220		Material	3M Adhesive	1	8	Pcs.