Master's Thesis

Cand.-M.Sc.: Borja Francés Martínez

Matr.-No.: 411840

Topic: **Methodology for the description of product usage in machinery and plant engineering**

Supervisors: Annika Becker

(RWTH Aachen University)

María Rosario Perelló Marín

(Universitat Politecnica de Valencia)

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Abbreviation	Description
2D	Two dimensional
3D	Three dimensional
CAD	Computer-aided design
cf.	Conferatur (compare)
CMS	Content management system
CNC	Computerized Numerical Control
CPS	Cyber-physical systems
CRM	Customer relationship management
CV	Customer value
DAG	Directed acyclic graph
e.g.	Exempli gratia: for example
ERP	Enterprise resource planning
ID	Identification
IoT	Internet of Things
ITU	International Telecommunication Union
KBE	Knowledge Based Engineering
KbeML	Knowledge based engineering Modeling language
KCCM	Knowledge Consolidation & Cross sectoral Management
LDB	Local database
M2M	Machine-to-machine
PLC	Product life cycle

PLM	Product lifecycle management
PUI	Product usage information
R&D	Research and development
RE	Requirement engineering
RM	Requirement management
ROI	Return on investment
SysML	Systems Modeling Language
UELZ	User Experience Landing Zone
UML	Unified Modeling Language
VDI	Verein deutscher Ingenieure
VOP	Virtual open platform

1 Introduction

This first chapter will cover an introduction for this thesis. In Chapter 1.1, the background and motivation for this thesis is developed to highlight the relevance of the topic and give an overview about the current situation and the resulting motivation for this work. Furthermore, the research aim is introduced in Chapter 1.2 and the whole chapter finishes with the thesis structure, detailed in Chapter 1.3..

1.1 Background and motivation

Product development in both machines and systems is currently facing a variety of new challenges. These new challenges are being caused by the main megatrends and drivers of global development in the last decades, which include a raise in the global population, an economic growth and an increase in globalization that leads to a growth in the social and economic interdependence of states.[1] All these trends and new challenges introduce a lot of pressure in companies by expanding the product complexity. This means, that they must increase the efficiency of their processes and production and become more flexible in order to adapt to these new changes.

In the majority of the markets or industries, the entry of new competitors and the appearance of overcapacities can produce an increase in the intensity of the competition, which leads to a shift in the market power to the customer side and an intensification in the price pressure.[2] At the same time, the life cycle of a product on the market reduces from year to year, not only in the case of products for consumer goods, but also the lifespan of industrial products and capital goods is becoming considerably shorter. [3] Moreover, another important factor that needs to be taken into account is the fact that due to the high competition, companies are being forced to reduce the time-to-market of their products and shorter the innovation cycles as a way to meet customer needs as fast as possible.[4] In this context, the development costs for products with both overloaded or seldom used product functions increase exponentially.[5]

Based on this initial situation, it is a key factor to improve the efficiency and effectiveness in research and development (R&D).[6] Particularly in the case of innovation process, companies want more than ever to launch their products into the markets rapidly, using as less resources as possible and maintaining a high probability of success. [7] The quick transformation of a customer need into a market solution has become one of the key success factors in a competitive market.

[1] Cf. Michels (2016), Vom Kunden zu Lastenheft, p. 165.
[2] Cf. Schuh and Riesener (2018), Produktkomplexität managen p. 15.
[3] Cf. Michels (2016), Vom Kunden zu Lastenheft, p. 170.
[4] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.
[5] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.
[6] Cf. Schuh (2013), Lean innovation, p. 7.
[7] Cf. Gommel (2016), Transparenz über den Innovationsprozess, p. 143.

Due to this necessity to fulfill customer´s needs as fast as possible, development activities are therefore targeted on those functions and characteristics that have an explicit positive influence on the fulfillment of these needs.

As it has been already mentioned, the efforts should focus on the early stages of the development of new products and specially on those functions which contribute positively to the satisfaction of customer requirements. To do so, knowledge about customer requirements is a necessary prerequisite to consistently implement these needs in technical products. In addition, these knowledge about customer needs or requirements will help to develop a more realistic usage hypothesis in the start of the product development phase. The usage hypothesis is a prediction of how the product is going to behave on the market and how customers will behave towards the product. It englobes all the assumptions that are made by developers in the first stages of the product during the R&D, therefore the more information obtained during the usage phase of the product will allow companies to obtain a more precise usage hypothesis.

Unfortunately nowadays, companies are facing the challenge that, during the product development, they often have little or no knowledge of which product functions the customer actually wants. Although the range of functions of most products is increasing all the time, it is still up to developers to think and develop them: full automation of R&D remains a vision of the future.[8] Surveying future customers is also not convenient, as they often do not know exactly how the product is supposed to work in the specific application during the usage phase. If customer feedback is received and used to focus product development - for example when optimizing the next generation of products - it is mostly unstructured and isolated feedback from dealers or service partners based on warranty cases, complaints, or product recalls.[9] Also, the usage information from previous product generations is not being exploited systematically to improve future product generations. [10] As a result, development activities and focuses are not systematized because they are based on assumptions about subsequent product use and the corresponding customer needs.[11]

This lack of product use knowledge during the development of the product means that developers do not know in which product functions they should focus to improve the product, hence customer needs are not fully satisfied. Therefore, the customer value decreases because it is not addressed by the new product.[12] The customer value is the "perceived value of the properties of a product for which the customer is willing to pay a certain price because the properties of the product provide him with a benefit arises". [13]

[8] Cf. Michels (2016), Vom Kunden zu Lastenheft, p. 164.

[9] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

[10] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

[11] Cf. Schuh (2013), Lean innovation, p. 7.

[12] Cf. Schuh (2013), Lean innovation, p. 39.

[13] Cf. Schuh (2013), Lean innovation, p. 39.

The lack of focus on the customer value and the customer needs often results in perfectionism and over-engineering. Over-engineering means that a product has more features or functions that the ones necessary for its intended use. These extra functions may be unnecessary, and they reduce the usability of the product making it over-complicated and potentially more expensive. Hence, product functions are designed here to the maximum extent technologically possible, without addressing the actual customer value. Even today it is often still present in the minds of development teams that maximum product functionality automatically leads to maximum customer satisfaction.[14]

As a consequence, over-engineering in product development makes the whole process much more inefficient because a lot of resources are focused on developing unnecessary functions which do not create customer value. All of this leads to a considerable waste of human and material resources. In addition, development goals, which are established basing themselves mostly in developer’s assumptions due to the lack of product usage information (PUI), are set prematurely and no longer questioned. Therefore, most of the time the generation of innovations in the development process, which contribute to meet customer needs and thus increase customer value, are discarded.

In order to validate the fulfillment of customer needs, agile development methods have become established in many places in mechanical and plant engineering.[15] As mentioned, these agile methods help to accomplish precisely, regularly and in a structured manner customer requirements. Another positive aspect of agile methods is the involvement of the customer in the validation of product increments for further development of the product during the development phase. The problem with these methods is that the product functionality cannot be fully validated under real conditions during the development phase. This is because some customer needs can only be identified during the actual practical use of the product in the usage phase, therefore these needs are not being taken into account in the product development. As a result, this means that using agile methods in product development can help to consider and include knowledge about the product in a methodical way, although this knowledge can only be generated to a limited extend.[16]

There is an enormous potential for gaining knowledge during the actual usage phase of the product under real conditions that is currently not being fully exploited, as shown in *Figure **1***. The data generated through the actual use of the product, allows a large gain regarding product knowledge. On the other hand, *Figure 1* also reflects that the use of this knowledge about the product often decreases abruptly when it is launched on to the market. The figure below shows two opposite curves that results in significant potential for product optimization, e.g., regarding product functionalities that are rarely used but costly to develop.[17]

[14] Cf. Schuh (2013), Lean innovation, p. 39.
[15] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.
[16] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.
[17] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 117.

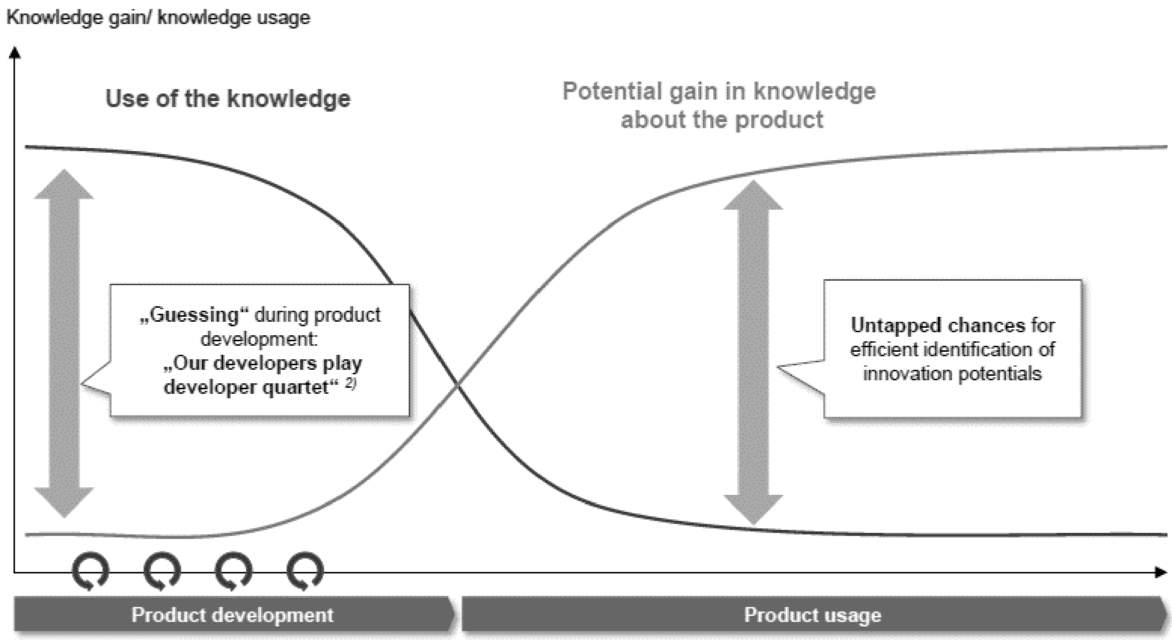

Figure 1: Potentials for product optimization by gaining knowledge in the usage phase.

To exploit all this generated knowledge during the product usage phase there is a trend to change from machines and systems in engineering plants into cyber-physical products and systems which enable access to information from the usage phase.[18] This is due to the fact that companies are shifting from selling products to providing product service systems. Also, the miniaturization of product-embedded sensors and their price degression and to advances in information technology facilitate access to usage information of current products, which can be used in future product generations.[19] The continuous analysis of the current status of the product and process will optimize and make easier for developers to detect which are the most important product functions that satisfy customer´s requirements and which functions are less used and could be excluded on the following product generations.

The information from the usage phase therefore serves, among other things, to gain insight into the actual use of the product functions and thus validate the product usage assumptions and hypothesis on which the development of these functions is based. If these assumptions deviate from the actual use of the products, knowledge about customer needs can be refined and decisions about possible functional optimization in the next product generation can be made on an informed basis. These decisions form an essential basis for product innovations and contribute significantly to the orientation of the next product development activities.

[18] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.
[19] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

1.2 Research aim

The objective of this work is to develop a methodology that will enable companies to use, in a methodical and structured manner, all the knowledge generated during the usage phase of machinery in engineering plants to improve the development and design of the product in the next generation.

The outlined research aim leads to the following main question of this research which will also serve as a guideline for the structure of the upcoming chapters:

“how can the product usage in machinery and plant engineering be described and modelled as a basis for the validation of assumptions from product development?”

In the scope of this thesis, a methodology for the description of product usage in machinery and plant engineering will be elaborated. In particularly, a modelling language appropriate for the holistic description of the usage cycle will be developed. Furthermore, a procedure for the analysis of functional requirements will be designed, so that only user-relevant product functions are taken into account. Finally, the types of variability that may exist within the usage cycle shall be derived. The methodology for the description of the product usage shall form the basis for the subsequent definition of the usage hypothesis.

This research will allow companies in the context of mechanical and plant engineering to identify potential for innovation from the analysis of information from the product usage. By identifying the innovations that are relevant to customers and that they satisfy their potential needs, product value can be generated. At the same time the consumption of resources and budget for functions that are unnecessary or not required by customers in the product usage are minimized. By doing so, the uncertainty during the early stages of the innovation process will be considerably reduced.

In addition, the presented work will grant manufacturing companies the opportunity of becoming more flexible, so they can subsequently adapt, and react more rapidly to changing circumstances in the market. The data generated during the usage phase of the product will serve as basis to improve future product generations.

1.3 Thesis structure

The presented thesis has been divided into six different chapters. In *Figure 2* the complete structure of the thesis with its content is illustrated.

The first chapter of the thesis provides an introduction to the topic by presenting the background and motivation. From there, a research objective is drawn to specify the contextual orientation of the following chapters. This is followed by an overview of the structure of the thesis.

In Chapter 2, the essential fundamentals and definitions for the development of the model are presented. For this purpose, the definition of Product Life Cycle (PLC) is provided with its seven differentiated phases. Due to the fact that the methodology to be developed focuses on the usage phase of the product, the definitions of product usage and product usage information (PUI) are provided. Then the terms of product functions and product model are emphasized to understand the different parts and functions that form a product. In addition, definitions of customer value and requirements are provided to better capture the real user needs. Finally, the concept of Industry 4.0 is introduced, focusing on the terms of cyber physical systems (CPS) and Internet of Things (IoT) which define the vision of future smart products that will be able to obtain information during their usage and communicate with other products or systems.

Chapter 3 performs a structured literature review of the existing approaches in the context of this thesis. Therefore, in this chapter the evaluation criteria with the object area and target area of this thesis will be defined. The evaluation criteria will form the basis for the requirements of the methodology developed in the next chapter.

In Chapter 4, the methodology for this thesis will be developed. The methodology will consist in three clear steps which will cover the target areas presented in the previous chapter. The first step of the methodology explains the modelling of the usage phase of a product. The second step describes the identification of the user´s requirements and links them to the relevant product functions. In the last step of the methodology, the product functions will be classified according to their type of variability.

In the fifth chapter, an evaluation of the methodology developed in the thesis will be performed. The methodology will be applied to the RoboxPRO 3D printer. First the printer usage phase will be modelled, then the most important requirements will be identified and matched to the printer´s product functions and finally the product functions will be classified according to their variability during the usage phase. At the end of this chapter the key insights from the evaluation will be discussed.

In the final chapter, Chapter 6, the conclusions of the thesis are provided. In addition, in the research outlook, the related fields for future research and possible extensions of the methodology are given.

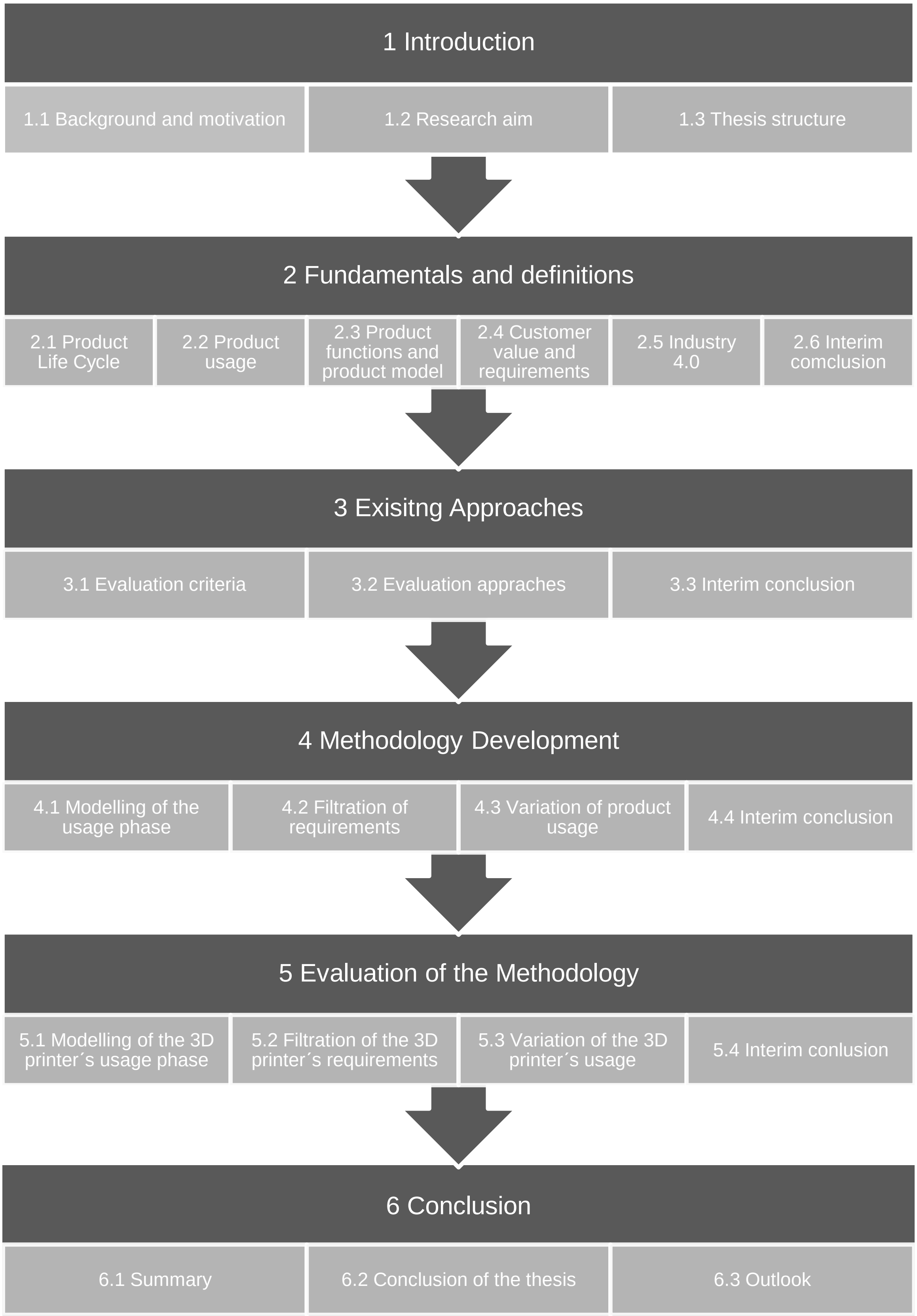

Figure 2: Thesis structure.

2 Fundamemals and definitions

In this chapter the fundamentals and definitions that are relevant for the presented thesis are going to be introduced. The following content forms the bases of the objective of the work, i.e., the development of a methodology that will allow to analyse and use the information from the product usage in order to improve the product itself in the early stages of the product development. First of all, in Chapter 2.1, the concept of Product life cycle (PLC) will be defined with all of its different phases from de conception till the retirement of the product. In the following section, Chapter 2.2, the term of Product usage will be defined in detail and the concepts of the Usage model and Product usage information (PUI). The third part of this chapter will illustrate the terms of Product functions and Product model. Chapter 2.4 will provide a description of what is the customer value and the importance of it and how it is related to the requirements. In the last Chapter 2.5, an overview of the model of Industry 4.0 is given focusing on Cyber-physical systems (CPS) and the Internet of Things (IoT).

2.1 Product Life Cycle

Product life cycle (PLC) is an important concept because it describes all the phases a product goes through in its entire life. It is crucial for a company to have a clear vision of the PLC of a product because the existence of competing products, market behavior and the environmental situation change over time. Therefore, having a well-defined PLC structure will help companies to adapt better to these constant changing situations. A definition of the term PLC and a description of all the different phases will be presented in this chapter. Moreover, the PLC from the marketing and sales perspective will also be presented to understand better how the product behaves and interacts with customers once it is on the market and during the usage phase.

2.1.1 Product Life Cycle definition

Product life cycle (PLC) is an important term which describes all the stages a product goes through from its concept creation until the retirement of the product of the market.[20] The success of a product is defined by the key activities in all phases of the PLC. When the product team gets aligned with this clear plan of activities, their objectives are complete, and they can therefore support products better in any phase of the lifecycle. As an outcome, this can produce several benefits, including increased profitability and greater sustainability for the company.[21]

All products, whether they are a good or a service, will pass through this distinct seven phases of the PLC, each one at their own time. The seven phases of the PLC consist of: conceive, plan, develop, qualify, launch, deliver and retire. The diagram bellow, *Figure 3,* describes the sequence of the seven phases that a product must go through during its complete life cycle.

[20] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 1
[21] Cf. Sergio Salimbeni, Product Life Cycle Management in Industry 4.0, p. 3

Figure 3: Seven phases of the PLC.

In addition, an overall understanding of how these phases fit together and that on occasion overlap will sharpen the company´s skills in developing product roadmaps for future products.[22] Having a better understanding by analysing product use information of how customers use the product, what benefits they expect from it and what attributes have a higher value for them, will allow to reduce the uncertainty in the early stages of a product´s PLC and therefore will increase the probability of success when launched into the market.

2.1.2 Phases of the Product Life Cycle

Conceive phase

The first step before starting the product development is to examine the market and this is done in the *conceive phase*. To develop this market research, companies must start analysing the trends in the industry and the competitors. To do so there are important market analysing tools such as, Porter´s Five Forces which serves to review the industry and environment. [23]

The Five Forces framework is a "useful starting point for strategic analysis even where profit criteria may not apply".[24] The interaction of Porter´s Five Forces is a permanent threat to the overall success of a company and after analysing these Five Forces, a company can assert on the attractiveness and profitability of the sector.[25] *Figure* 4 represents Porter´s Five Forces.

Figure 4: Five Forces Framework.[26]

[22] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 1
[23] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 2
[24] Cf. Gerry Johnson et al. (2008), Exploring Corporate Strategy, p.60
[25] Cf. Fabian Dälken (2014). Are Porter's Five Competitive Forces Still Applicable? A Critical Examination concerning the Relevance for Today's Business, p. 3
[26] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 2

In addition, companies have to take into consideration the improvements and shifts in industry technology. Technological advances can reshape the way the product is manufactured, sold, or used by customer. Another tool that can be used is the PESTLE analysis which examines the current political, economic, socio-cultural, technological, legal, and environmental factors.[27] The figure below shows an example of this analysis method.

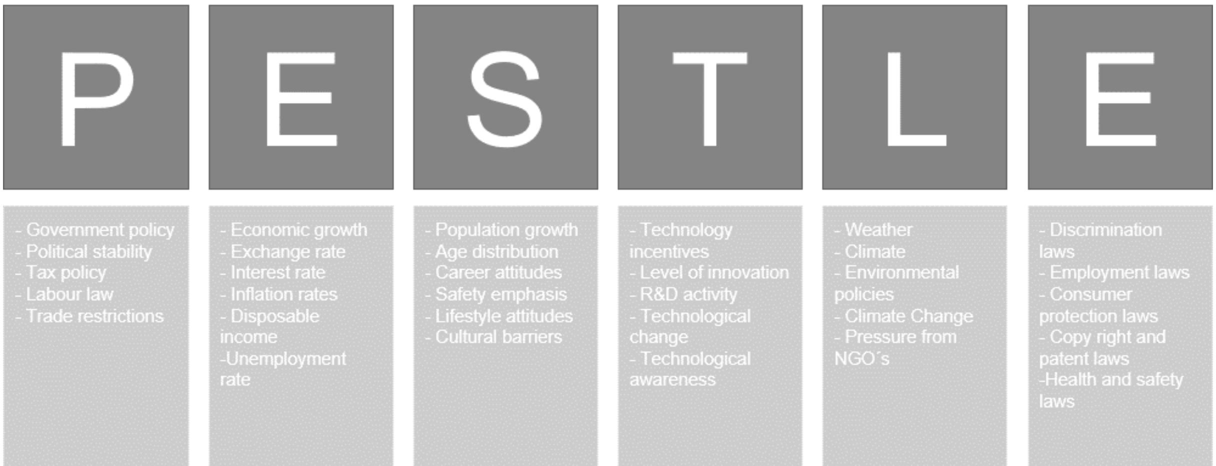

Figure 5: Example of PESTLE analysis method.[28]

Plan phase

During the second phase of the PLC, the *plan phase,* the team must develop a roadmap that takes into consideration all aspects of the product like its design, resources available, requirements, etc. To build a roadmap there are eight steps to follow:

1. Decide on the detail level.
2. Assess competitors and trends.
3. Prioritize requirements.
4. Designate a time frame.
5. Select an organization strategy.
6. Create an internal roadmap.
7. Collect buy-in and finalize.
8. Develop an external roadmap.

It is often during this stage that the whole idea of the product changes. The initial product development sets an intention, but the real purpose is only revealed once the logistics and resources are considered and implemented.[29]

[27] Cf. Gerry Johnson et al. (2008), Exploring Corporate Strategy, pp. 55-57
[28] Cf. Gerry Johnson et al. (2008), Exploring Corporate Strategy, pp. 56
[29] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, pp. 2-3

Development phase

Once the plan is clearly defined and completed, the next stage in the PLC is the *development phase*. The main priority here is scheduling because it is essential to have clear and defined deadlines for both the engineering and sales team. To have a well-structured development phase of a product it is important to select a strategy depending on the company goals, budget constraints and the product itself. There are three main developing strategies: Theme-based strategy, golden features and time released strategy.

A theme based organising strategy requires that similar, high scoring features are collected and grouped together. Each grouping is assigned a theme, such as product performance, and a release deadline. Implementing themes helps to protect against feature proliferation. Sub-themes can be used, but they tend to undermine the overall strategy.

The second strategy is the golden feature. This is a relatively simple plan that consists of selecting one main feature for each product version. All marketing and development resources should be targeted on the golden feature. Applying this strategy also prevents feature proliferation. However, independently of the circumstances, when using this strategy, it is not possible to launch without the golden feature.

The last organisational strategy is the timed release. Contrary to the previous plans, the timed release is based on dates, not features. Average release dates are set quarterly or every six months. It is essential to prioritise in order to meet deadlines because if the team misses a deadline, it needs to be refocused and work to achieve the release by the next one.

Independently of the chosen strategy it is essential in this phase to consider and be aware of the shifts and fluctuations in the market. Companies need to adjust the product plans because customers priorities and needs are constantly changing.[30]

Qualify phase

This fourth stage, defined as *qualify phase,* ensures that the product is on the right track and the previous stages have been carried out properly. There are three main methods that can be applied to qualify the product, which are beta testing, focus groups and internal feedback.

Beta testing requires constant checking with the testers to collect feedback about the product. Here it is important to organize the information and critiques provided from the feedback and develop actions to correct and improve the product. Moreover, it is essential to have periodic revisions to adjust the product from the deviations.

Another way to qualify is through interviews or focus groups where information can be gathered from consumers and used to improve, change the product if it does not accomplish user´s standards. It is important to eliminate all potential distraction, such as physical or biological distractions, during this process to ensure that the feedback information is as bias as possible.

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[30] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 3

The final way to rate the product is to request internal feedback. Service and customer teams play a key role because they are often the first point of contact between the customers and the company. They directly hear the issues that customers may have with the product and their insight can be used to find out if the product meets the customer´s intended needs.

In conclusion, in this qualifying phase all the information gathered must be communicated to the engineering team so it can be used to improve or correct the product, set up additional deadlines and develop new features.[31]

Launch phase

The next phase is the *launch phase* and at this stage is where the product finally reaches the market. The launch includes the market announcement and the decisions around the initial availability and exposure of the product.

There are several factors that influence the customer when purchasing a product. These influencers are self-image, memory and learning, relationship with brands, beliefs and attitudes, emotional state, and communication.[32] They all influence how the customer interprets and perceives product launch messages and advertisements.

Additionally, it is important to understand that in the launch phase the selling of the product is not the primary goal. Customers do not purchase a product because they have been ordered to do so, they have to want the product.[33] The aim of the market launch is to share the value of the product to increase the customer's desire to buy it and therefore the chances of selling it.

Deliver phase

In this sixth stage of the PLC the product is in the *deliver phase*. In this phase products are on stores, consumer´s homes and in workplaces. The delivery phase of the PLC includes maintenance of current programs, frequent measurements of the return on investment (ROI), and product optimization.[34]

Regarding product optimization here is where the company can gather feedback information of the real usage of the product. As presented in the first chapter there are several ways that the information in the usage phase can be extracted, like cyber-physical products, sensors or customer survey.[35] This information can be used by companies to improve future product generations and to focus on the features that are more important to customers in order to increase the product value.

[31] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 4
[32] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 4
[33] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 5
[34] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 5
[35] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

Retirement phase

The *retirement* is the seventh and final phase in the PLC. The reason a product is retired from the market is that sales and performance of the product decrease in comparison to other products from competitors and it can damage the image of the company and its future growth. In this stage, it is essential to accomplish a successful product retirement with the least amount of negative consequences.

Once the product is retired, if the company wants to continue in the market, they can transition from one product to another. All the information and experienced gained in all the stages of the PLC must be used in this new product generation to produce a better and more successful product. [36]

2.1.3 Product Life Cycle from the marketing and sales point of view

From the marketing perspective, once the product is launched into the market, the PLC is described by the market as a function of time. The exact definition of PLC is expressed as “the long-term aggregate demand of all the brands that comprise a generic product category. A life cycle can be represented by graphing the aggregate sales volume of a product category over time, commonly in years.”[37]

In this case the PLC is seen as the time taken from product launch, through the phases of growth and maturity, to the decline in demand.[38] In *Figure 6* the demand is reflected in the vertical axis in terms of sales and the four stages of the PLC are represented on the horizontal time periods. The graph shows how the sales vary along the different phases of the PLC.

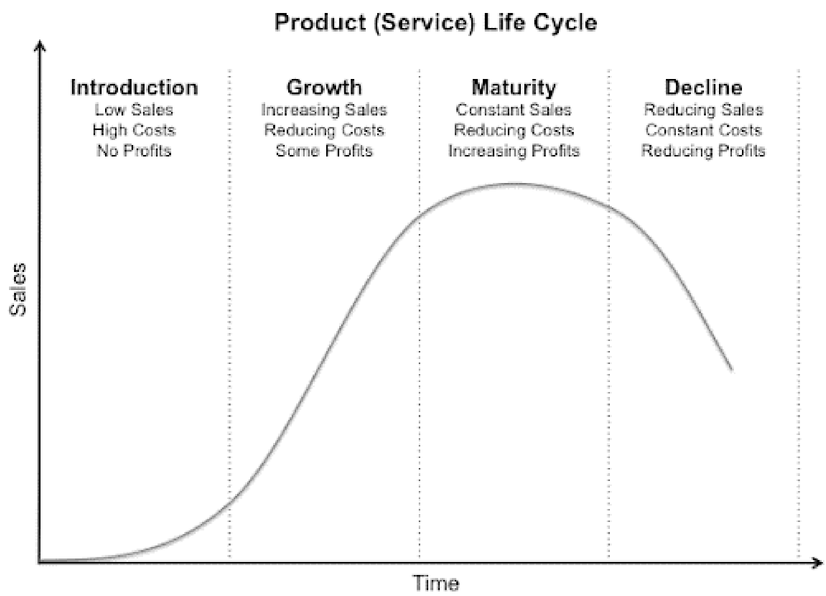

Figure 6: Product life cycle (Marketing and sales point of view).[39]

[36] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle, p. 6
[37] Cf. Etzel et at. (2015), Fundamentals of Marketing, p.22
[38] Cf. Sergio Salimbeni, Product Life Cycle Management in Industry 4.0, p. 3
[39] Cf. Sergio Salimbeni, Product Life Cycle Management in Industry 4.0, p. 5

As mentioned above, there are four accepted phases in the life cycle of a product: introduction, growth, maturity, and decline. The introduction phase usually consists of a significant investment in advertising and a marketing campaign that focuses on raising awareness of the product and its benefits to consumers. Here the goal is to develop a market for the product and create product awareness.

If the company's product is successful, it proceeds to second stage, the growth phase. In this phase there is a significant increase in the demand that produces a growth in the production and an expansion in availability. This means that the product has been accepted by the users and companies need to increase market share. In the case of innovative products there is a low competition in this early phase, so pricing can stay at a higher level.

The next phase is the maturity phase, and it is the most profitable stage and here the producing and marketing costs decline. At this stage, the sales will also level off due to an increase in competition, so product features must be upgraded to maintain the market share. As mentioned, production costs tend to decrease in the maturity phase as a result of a more efficient manufacturing process.

Finally, the product reaches the decline phase where there is bigger increase in the competition due to new innovations or features in competitor´s products or to a reduction in the prices. Another factor that can affect the revenue at this point is a change in the customer’s needs or the appearance of new products that fulfil better these needs. At this stage, the product is at the end of its life cycle, and it loses its market share and start its decline.

2.2 Product usage

The information that serves as a basis for the identification of innovation potential in the context of this research is obtained from the product usage phase. Chapter 2.2 therefore defines the types and characteristics of product usage and how the information obtained from this stage can be used to develop future generations.

2.2.1 Definition of product usage

Product usage is an important factor of consumer behavior and there is an enormous potential in extracting and using product usage information (PUI) to improve next product generations. Product usage refers to the stage when consumers are using the product after they have purchased it. How consumers use their products can be analysed from three different perspectives: social interaction perspective, experimental consumption perspective and functional utilization perspective.[40]

- The **social interaction perspective** focuses on the symbolic aspects of usage. It analyses the social meanings attributed to the consumption of intangible product attributes in the case of socially conspicuous goods such as cars and houses.

[40] Cf. S.Ram (1990), The Conceptualization and Measurement of Product Usage, pp. 67-68.

- The **experimental consumer perspective** focuses on post-purchase use, particularly consumer experiences like " fantasies, feelings and fun".
- The **functional use perspective** discusses the use of product attributes in several different situations.[41]

From the perspectives mentioned, the functional use perspective is the most important of the three. Consumers are more likely to use the attributes or features of a product after they have purchase it. There is a wide range of useful information in the post-purchase stage where the product is being used, especially in those products based on technological innovations. [42]

As mentioned above, the product use phase offers enormous potential for specific product development through product optimization and innovation that leads to a continuously increasing product value. [43] This concept is illustrated in *Figure 7.*

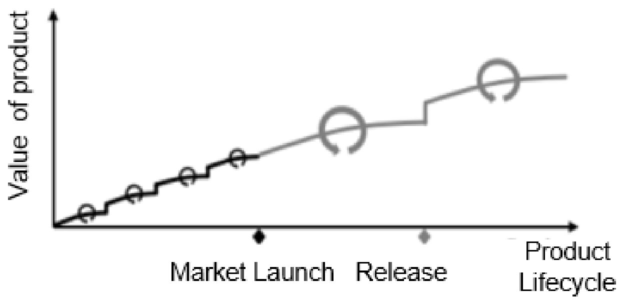

Figure 7: Continuous increase of the product's value through optimization and innovation.[44]

Product use data can be used as a continuous feedback source for development, so that the acquired knowledge is used to perform short cycle releases in operation. In physical products, particularly in the sector of machinery and engineering plants, the contribution of product usage data to development is becoming increasingly important. Machines and plants are being converted more and more into so-called cyber-physical products (CPS), where they are connected to one another and to the global network by communication systems. This will allow them to use the data extracted from the product usage in the next generation of products.[45]

Furthermore, most of the products on the market start their life by providing an innovative functionality to users. Afterwards, products often become commodities and price becomes the major factor of differentiation among competitors. Product usage helps to develop new innovations that prevent products from reaching the commodity status. Therefore, product usage evolves over time, creating new opportunities for unfilled needs and desires. It also contributes to the user´s satisfaction and creates brand or product loyalty.[46]

[41] Cf. S.Ram (1990), The Conceptualization and Measurement of Product Usage, pp. 67-68.
[42] Cf. S.Ram (1990), The Conceptualization and Measurement of Product Usage, p. 68.
[43] Cf. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 191.
[44] Cf. Micheal Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p.191
[45] Cf. Micheal Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 192.
[46] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 35.

2.2.2 The usage model

The usage model can be described as a collection of data that describes a system usage for a particular context. The model describes the user and system interactions and identifies the benefits of the system to the user.[47] According to SIMMONS the exact definition of the usage model states that "a usage model describes the interactions between the user and the system at a level that identifies the system's benefits to the user".[48]

This model takes into consideration the impact of usage, business, and technology on a product. The term usage bridges the gap of the product´s technology and business perspective. The business-usage intersection describes how the usage of the product affects the market size, segment share, product message and competitive advantage. The use-technology intersection connects the use of the product with its architecture, components, and features. [49] *Figure 8* illustrates the interaction in product development between the three terms mentioned.

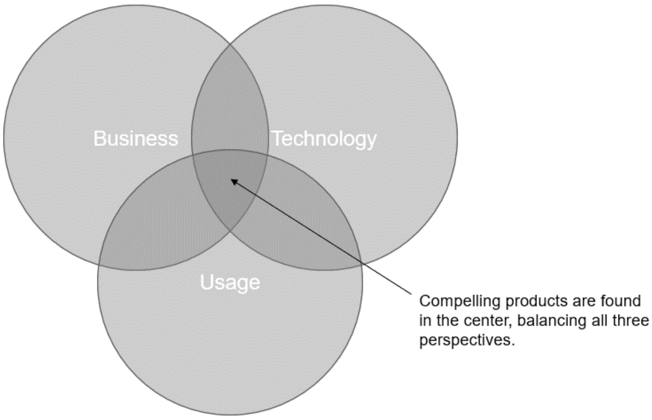

Figure 8: Relationship between Usage, Business and Technology in product development.[50]

2.2.2.1 Usage model structure

As already mentioned, the usage model defines product usage in a specific context. The structure of this model consists of three main tiers: supporting data, overview data, and usage details. A usage model usually starts in a planning organisation, which consist of a name and a brief description paragraph. As the model evolves, planners and user-centred design specialists collect supporting information and produce a usage summary. Ultimately, they add usage details to complement the model. But in terms of volume of information, the model is similar to a pyramid with supporting data at the bottom, usage details in the middle, and the summary at the top.[51] The following figure represents the structure of the usage model.

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[47] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 34.
[48] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 1.
[49] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 35.
[50] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 35.
[51] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 35.

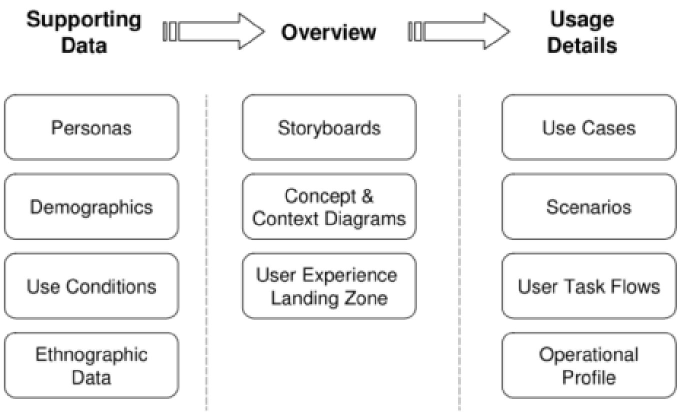

Figure 9: Overall structure of the usage model.[52]

The first layer of the usage model structure consists of the supporting data level and its purpose is to provide with background and depth to the levels above. It consists of information that induces the priority, context, and source of the usage data. *Figure **9*** also shows, the supporting data level contains the following components:

- **Personas:** They are the real users of the product, and they serve as help in the design, test assumptions and they validate design decisions.
- **Demographics:** It gives support to the usage model by providing it with prevalence information, population sizes, segment comparison and purchase intentions.
- **Use conditions:** They consist of environmental conditions derived from the product use context. These conditions are used to evaluate different competing designs and technologies and they prevent both over-engineering and under-engineering products.
- **Ethnographic data:** Represents the relevant cultural aspects, norms, and other data.[53]

In the second level of the model, you find the usage overview level, which is based on the information from the supporting data level. The purpose of this the information from this level is to create an introduction or guide to the main structure of information contained in other levels. The usage overview data is important in communicating with other product development teams and management reporting. This level consists of the following elements:

- **Storyboards**: they illustrate the process of how to use properly a product and provide a user interface to the information that is extracted from the usage phase. Storyboards are useful in the early stages of product planning because the effectively illustrate the whole product concept.
- **Context diagrams**: they reflect how the system interacts with other systems, like its system environment, and represents the system itself as individual entity.
- **Concept diagrams:** they show an overview of the overall system and its use in only a one phase.

[52] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 2.

[53] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 2.

- **User experience landing zone (UELZ):** draws attention to outstanding, objective and minimum user experiences in a simple format. It used to summarise the product's use and status in relation to objectives and also to documents the “goodness” for user experience. [54]

The peak layer of the usage model consists of the usage details level. This level serves to manage scope based on usage, provide data for establishing quality requirement objectives, validate architectural decisions and elaborate product documentation. The usage details level contains the next components:

- **Use case**: they are used in the usage model to define and specify a sequence of interactions between the system and the actors.
- **Scenarios**: they consist in texts which contain contextual details of the usage description. Scenarios server for testing and reviewing components of product usage.
- **User task flow**: they illustrate graphically the usage flow through a set of tasks.
- **Operational profile**: refers to the operations that can be carried out with a device or computer program, and the relative probabilities of each operation to take place.[55]

2.2.2.2 Benefits of the usage model

The usage model offers several advantages and benefits and that is the reason that it has been adopted on several platform and product development projects. According to SIMMONS all these benefits brought by the model provide billions of dollars in projected revenue.[56]

First of all, the usage model helps to clarify and correct necessary and intended usage in new and existing areas. These clarifications and corrections usually occur in places where customer needs were thought to be fulfilled. All of this minimizes the development cost and therefore it increases the revenue.

Moreover, models serve as platform for the requirements in the usage phase. Platform requirements are traceable to the usage model and its components, being part of a complete specification of the requirement´s source, justification, and priority. It allows the evaluation of many assumptions when the usage hypothesis is formed.

In addition, it helps to develop a user centered design in the planning and development phases. The usage model translates the business requirements into technology requirements. It also defines concepts and vocabulary and exposes the necessity for additional work. [57]

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[54] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 3.

[55] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 3-4.

[56] Cf. E. Simmons (2005), The Usage Model: A Structure for Richly Describing Product Usage during Design and Development, p. 5.

[57] Cf. E. Simmons (2006), The Usage Model: Describing Product Usage during Design and Development, p. 35-37.

2.2.3 Product usage information

Product usage information (PUI) is the knowledge extracted from the usage phase that can contribute to enrich the whole production process and the final product itself. PUI can be used as feedback to support the design of upcoming product generations and can be either objective or subjective.[58]

Subjective data is information from the client's point of view ("symptoms"), which includes feelings, perceptions, and concerns. The systematic acquisition and analysis of retrospective subjective customer data is facilitated by some marketing-based approaches such as customer surveys, quality function development and Kano methods. The problem with this kind of data is the existence of possible biases in these self-report instruments that could raise doubts about the validity of the measurement conducted.[59]

On the other hand, objective data refers to measurable data and observable (“signs”) obtained through physical examination, observation, and laboratory and diagnostic testing. This type of information tends to be more independent of biases.[60] Objective field data, like the obtained from sensor, operational or service data, is barely available, collected or used.[61] As a result of advances and the lower price of sensors integrated into micro-products, more and more companies are using product field data to provide condition monitoring solutions to support preventive maintenance of critical parts.[62] Various research approaches considered further uses of this data to optimise product operation planning, as well as to extend product lifetimes and improve the ecological impact of product usage.[63]

Another way to classify the type of information extracted to optimize the whole process is depending on where this information comes from. The following table shows all the sources of information considered.[64]

[58] Cf. Abramovici (2011), Providing product use knowledge for the design of improved product generations, p. 211.
[59] Cf. Dirk Tempelaar (2020), Subjective data, objective data, and the role of bias in predictive modelling, p. 1.
[60] Cf. Dirk Tempelaar (2020), Subjective data, objective data and the role of bias in predictive modelling, p. 1.
[61] Cf. R. Teti (2010), Advanced Monitoring of Modern Operation, p. 717-739.
[62] Cf. Abramovici (2011), Providing product use knowledge for the design of improved product generations, p. 211.
[63] Cf. Krause (2007), Product Lifecycle Planning and Tracking, p. 183–192.
[64] Cf. Abramovici (2011), Providing product use knowledge for the design of improved product generations, p. 211.

Information type	Example
Product instance use	Incidents: faults, cracks, leaks, breakdowns
	Operation parameters: operation duration and cycles, rotation speed, temperature
	Resource consumption: energy, material
Product instance workspace	Parent assembly or neighbour influencing parts
Product instance operation	Environment information: temperature, noise, humidity, vibration
Product service data	Repair, maintenance, overhaul events, replacement of parts
Product user/operator data	Personnel data, qualification, workload

Table 1: Considered product use information.[65]

In addition, all the information that is extracted from the usage phase will help to develop a hypothesis of use, which will more closely resemble reality as it is based on information about the actual use of the real product. Furthermore, thanks to the extracted PUI there will be less discrepancies between what has been previously planned in the hypothesis and the reaction of consumers once the product is on the market.

2.3 Product functions and product model

In this Chapter 2.3 the terms of product functions and product model will be described in detail. The first concept refers to all the features or attributes thar form the product and the second term is an abstract representation of the product.

2.3.1 Definition of product functions

The term function describes the relationship between an input and output of a system with the purpose of fulfilling a specific task. The whole task of the product is defined by the overall function which is divided into several different sub-functions. The linkage of these sub-functions to the overall function can be expressed in the function structure.[66]

All the subfunctions that form the overall function can be classified as main or basic functions and secondary functions. The main functions are all those sub-functions that contribute directly to the fulfilment of the overall function. They are those functions which are essential to the customer and the reasons for which the user or purchaser acquires the product.

[65] Cf. Abramovici (2011), Providing product use knowledge for the design of improved product generations, p. 211.
[66] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.

On the other hand, functions can be classified as secondary functions and these functions contribute indirectly to the overall function. Secondary functions are of no interest to the user, and they will only focus on the main functions of the product.[67]

In theory, all functions of a product can be subdivided into other functions, so therefore the lowest level of the function structure is made up only of functions that cannot be broken down into other functions. These functions that cannot be subdivided are generally known as functions of general application and they consider the relation between the input and output of a system in terms of variation in size, type, number, or time.[68] *Figure 10* illustrates the definition of these type of functions.

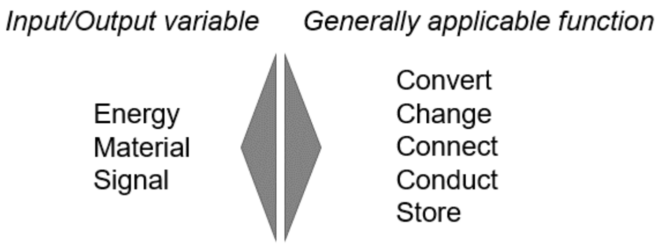

Figure 10: Generally applicable functions definition.[69]

In addition, product functions summarize all the supposed characteristics assumed in the product usage hypothesis. Therefore, all the relevant product functions are included in the usage hypothesis.[70]

2.3.2 Definition of product model

A model is defined as a representation of an approximation to reality with the aim to fulfil a specific purpose. Hence, models divide the essential aspects from the non-essential by drawing reality into simplified images of reality.[71]

A product model consists of all the relevant information that is created during product development and describes the entirety of the product. The product model represents an abstraction of the product and does not take into consideration any time dimension. It can be served to structure and classify different models at different levels with an increasing concreteness and complexity degree.[72] *Figure 11* is a representation of a product model in form of a pyramid.

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[67] Cf. M. Aurisicchio, ON THE FUNCTIONS OF PRODUCTS, p.2

[68] Cf. J. Feldhusen and K.-H. Grote (2013), Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung.

[69] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.

[70] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.

[71] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.

[72] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.

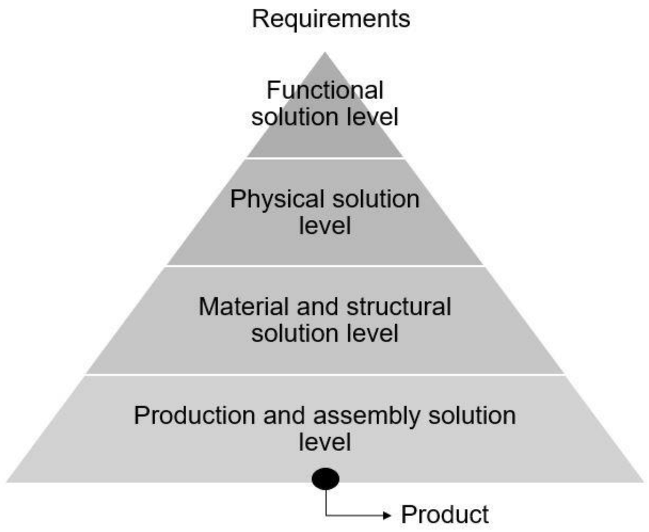

Figure 11: Product model pyramid. [73]

The peak of the product model pyramid represents customer´s requirements that are the features and attributes that the product needs to have. The next two levels describe the functional solution and the physical solution, i.e., how the product will meet the needs of the customer and the design of the product itself. The material and structural solution level determines the suitable materials and structural design for the product. In the lower level of the pyramid, the production and assembly solution level can be found, where the whole manufacturing process in order to obtain the final product is detailed.[74]

Functional models are part of the product model, and they provide the highest abstraction and serve as a base for more specific designs in the progression of product development. The goal of functional modelling is to define at first an abstract, and consequently solution-neutral overview of the overall function of the product and the derived sub-functions.[75]

2.4 Customer value and requirements

It is important to understand the terms of customer value and customer requirements because they define what the users really expect from a product or service and which attributes helps a product to differentiate from other products in the market. Once customer requirements are fulfilled it will produce an increase in the perceived value that users have from the product. Customer value and requirements should be considered in the product usage hypothesis in order to improve next product generations.

[73] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 193.
[74] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 194.
[75] Cf. S. Gramlich (2013), Vom fertigungsgerechten Konstruieren zum produktionsintegrierenden Entwickeln.

2.4.1 Customer value

The value concept is one of the key elements of marketing theory. The identification and creation of customer value (CV) is considered an important prerequisite for the company's future success.[76] It is crucial to understand how customers judge and value a service or product to gain a competitive advantage and gain market share. The aim of CV research is to describe, analyse and empirically evaluate the value that companies create for their customers and to link this information to other marketing concepts.[77]

According to GRAF, there two theoretical different perspectives or approaches to define the CV for a product or service:

- **CV from a company perspective**: Customer value is fundamental for the provider. The aim is to assess the attractiveness of individual customers (customer lifetime value) or customer groups (customer value) from the point of view of the company. This area of research is tightly related to relationship marketing, which seeks to develop and maintain beneficial business relationships with targeted customers.
- **CV from a customer perspective**: The emphasis is placed on the value generated by a company's product or service, as it is perceived by the customer, or on the achievement of the customer's satisfaction and desires by the company's products.[78]

In order to increase the CV for a product the company needs to be able to evaluate the customer´s experience. It is crucial to analyse all the steps and interactions customers take after buying the product to look to the attributes of the product that are perceived as beneficial and the ones that may cause dissatisfaction among customers. To do so it is important to collect and analyse information during the product usage phase as mentioned before in *Chapter 2.2* in order to increase the CV for the next product generations as shown in *Figure 7*. By collecting both qualitative and quantitative data from the usage phase, it will capture the voice of the customer, helping the company to improve and optimize the next product generation resulting in an increase of the CV of the product.[79]

In addition, it is important to clarify the relationship between value, quality, and satisfaction to understand better how by increasing the quality of the product or the satisfaction of customers also leads to an increase in the value of the product. *Figure 12* represents the conceptual delimitation between these three terms mentioned.

76 Cf. Albert Graf and Peter Mass (2008), Customer value from a customer perspective, p. 1.
77 Cf. Albert Graf and Peter Mass (2008), Customer value from a customer perspective, p. 2.
78 Cf. Albert Graf and Peter Mass (2008), Customer value from a customer perspective, p. 3.
79 Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, p. 191.

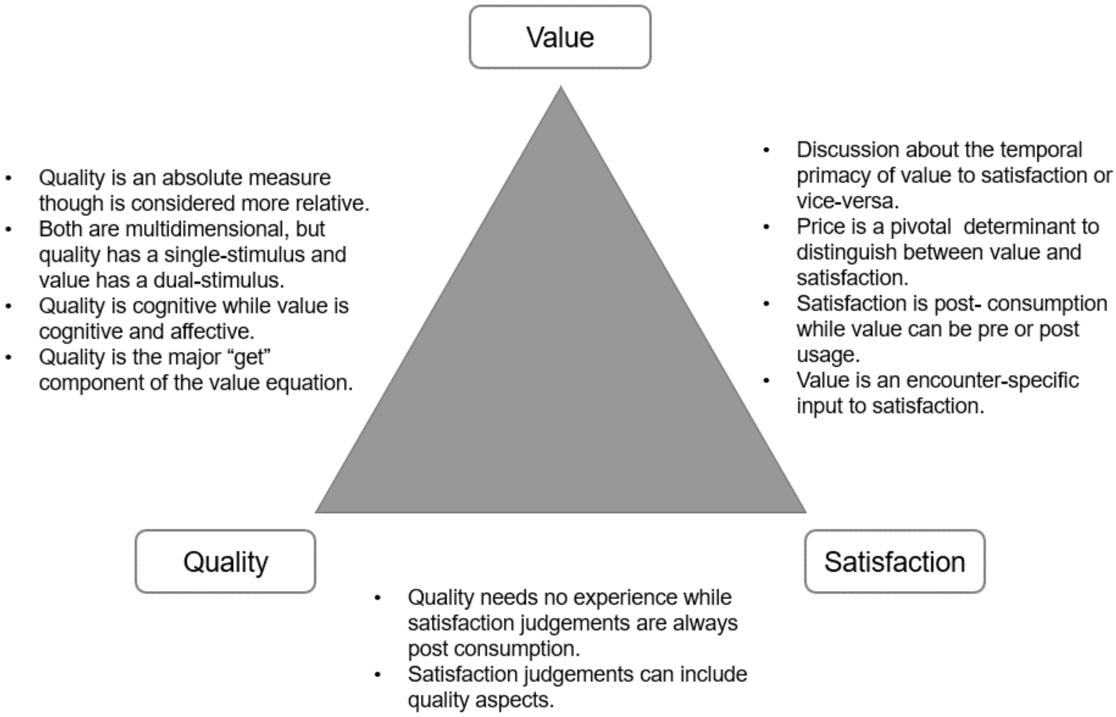

Figure 12: Conceptual relation between value, quality, and satisfaction.[80]

By comparing the terms of quality and satisfaction, it can be seen that quality is not experienced-dependent, whereas satisfaction judgements are always post-consumption of the product and based on the experience. Moreover, quality factors are clearly specific and cognitive based, while satisfaction judgement are both affective and cognitive. Quality can be also described as an absolute measure, but the value or satisfaction depend on more subjective perception from customers point of view.[81]

As mentioned, both terms value and satisfaction are more subjective than objective in comparison to the quality of the product but there are some differences between them. Firstly, the satisfaction that a customer gets from the product comes always after purchasing it, but the perceived value of a product can be pre or post use. Also, the level of satisfaction is generally independent to the price paid whereas the value a customer gives to a specific product is more price dependent. This is due to the fact that customers may associate high prices to high quality products, hence customers tend to give a higher value to products which are more expensive.[82]

[80] Cf. M. G. GALLARZA et al. (2011), The value of value: Further excursions on the meaning and role of customer value, p. 184.

[81] Cf. M. G. GALLARZA et al. (2011), The value of value: Further excursions on the meaning and role of customer value, pp. 184-185.

[82] Cf. M. G. GALLARZA et al. (2011), The value of value: Further excursions on the meaning and role of customer value, p. 185.

2.4.2 Definition of requirements

Requirements are driven by the needs of the customer or stakeholder. Needs, also known as goals or objectives, are the starting point for the formulation of a requirement. "A need is the result of a formal transformation of one or more concepts into an agreed-to expectation for an entity to perform some function or possess some quality.” [83] Following this definition, the initial necessities are converted into technical and business requirements. In the context of this thesis, requirements are defined as a functional or operational feature or restriction of a product.[84]

2.4.2.1 Attributes of requirements

To more precisely describe requirements so that they can be used during the development process, attributes are given to each requirement. Requirement attributes are identified by a name, their semantics and the attribute's range of values.

Requirements can be determined according to the IEEE 1233-1996 standard on the basis of the following attributes:

- **Identification:** Each requirement must be unique and can be identified with a number, name, or mnemonic.
- **Priority:** The priority of every requirement needs to be established, but its scale can be metric or simple scheme (High, Medium, Low).
- **Dependency:** They should only be defined when it exists between requirements
- **Risk:** Risk assessment techniques can be applied to develop a ranking of system requirements in accordance with their consequences or the level of risk prevention.
- **Source:** The original source that identifies the origin of the requirement should be indicated.[85]

2.4.2.2 Types of requirements

A distinction can be made between various types of requirements, such as functional, performance, restrictions, interface, or other requirements. First of all, functional requirements define a specific function that must be fulfilled in order to achieve the system's objectives. These requirements have normally the structure of an actor, a verb which describes an action and the object on which the actor and action acts on. Performance requirements contain information on the degree to which a system fulfils a function by defining a target to be achieved, giving a specific unit, e.g., 500 Kg. In addition, restriction requirements set criteria that cannot be modified without affecting product performance, production costs or time schedule. Interface requirements are those requirements that deal with the interdependencies between the components of the system.

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[83] Cf. SO/IEC/IEEE 29148:2011, p. 17
[84] Cf. Cf. SEBoK (2019), System Requirements
[85] Cf. SO/IEC/IEEE 29148:2011, p. 13

2.4.2.3 Requirement engineering

The term requirement engineering (RE) is defined by ISO/IEC/IEEE 29148:2011 as the interdisciplinary relationship between the supplier and the procurer of the requirements "to maintain and establish the requirements in the system, software or service of interest”.[86] RE focuses on determining, developing, analysing, documenting and managing requirements which provide an overview understanding to all interested parties and ensure that the real important needs are met.[87] The objective of RE in the product development process is to systematically identify requirements, document them, and then validate and adjust the requirements and monitor these documented requirements along the product lifecycle.[88] Another goal of RE is to minimize errors in the early stages of product development increase the quality of the product by identifying and eliminating potential risks.[89]

The four main RE tasks can be distinguished:

- **Collect requirements** from all interested parties through different techniques and sources.
- **Document requirements** properly through modelling languages.
- **Verify and validate the requirements** as soon as possible to make sure that the quality criteria of the requirements have been fulfilled and that the requirements are correct and complete.
- **Manage requirements**, which supports the above tasks and guarantees that the requirements are structured, coherent and achievable.[90]

Requirement collection

The first stage of RE is requirements collection, which is needed at the start of any project. This is generally done through interviews or workshops, feedback on existing products, questionnaires or other methods.[91] The aim is to obtain a textual statement of the objectives, requirements and expected boundary conditions.[92]

Requirement documentation

After identifying the requirements from customer and other interested parties, it is necessary to document them. The principal objective of this documentation phase is to make sure that the requirements are properly structured for the system. Documentation can include documents written in natural language as well as formal techniques like use case diagrams. [93]

[86] Cf. SO/IEC/IEEE 29148:2011, p. 16.
[87] Cf. SO/IEC/IEEE 29148:2011, p. 16.
[88] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, pp. 4–5.
[89] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, p. 2.
[90] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, pp. 4–5.
[91] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, p. 26.
[92] Cf. Holder et al. (2017), Model-Based Requirements Management in Gear Systems Design Based on Graph-Based Design Languages.
[93] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, p. 35.

Documentation is normally done by means of a System Requirements Specification (SRS), to translate customer needs into system specifications.[94] IEEE 1233-1996 describes the following nine properties that must be taken into account when developing a system requirements specification:

- **Unique:** Each requirement must be only indicated once.
- **Normalized:** Requirements must not overlap, which implies that a requirement must not be related to another requirement.
- **Linked Set:** Relationships between requirements should be clearly stated to reflect the dependencies among the requirements of the entire system.
- **Complete:** All the requirements should be stated to define properly the system.
- **Consistent:** There should be no contradiction between the different requirements of the SRS.
- **Bounded:** The SRS must describe explicitly the boundaries, extend and context for each set of requirements.
- **Modifiable:** The requirements within an SRS should be modifiable.
- **Configurable:** Versioning must allow to save and maintain different versions.
- **Granular:** The abstraction level of the system should be defined.[95] [96]

Alternatives to textual requirements can be diagrams, such as templates and modelling approaches.[97] In the following *Figure 13* the difference between modelled requirements and text-based requirements is represented.

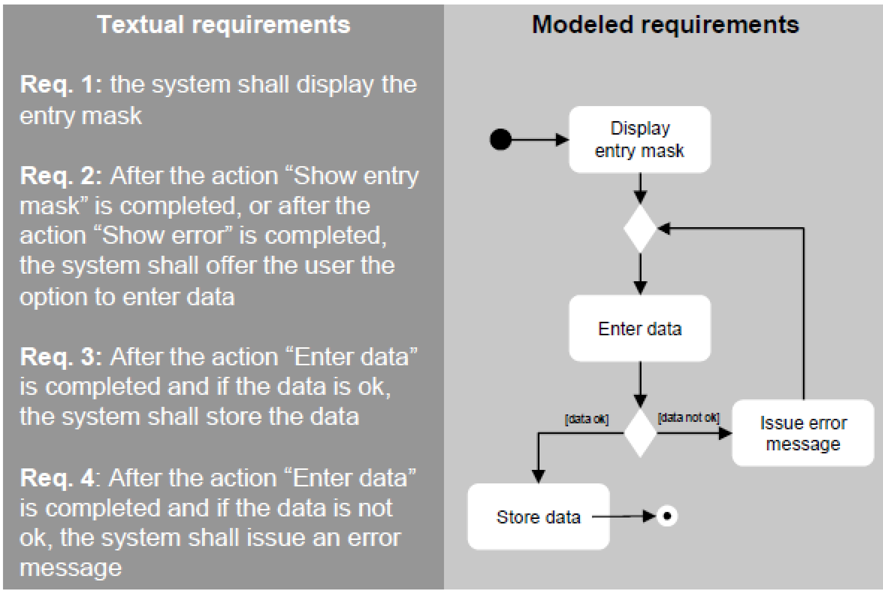

Figure 13: Textual requirements vs. Modelled requirements.[98]

[94] Cf. (1996), IEEE Guide for Developing System Requirements Specifications
[95] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, p. 36
[96] Cf. (1996), IEEE Guide for Developing System Requirements Specifications, p. 5
[97] Cf. Pohl et al. (2015), Basiswissen Requirements Engineering, p. 37
[98] Cf. Friedenthal et al. (2015), A Practical Guide to SysML, p. 309

In addition to supporting text-based requirements modelling, the requirements diagram highlights the relationship within the requirements and the elements of the model that fulfil the requirement and the model test cases that validate the requirement.[99] It enables the modelling of requirements in a graphical, tabular, or tree-structured manner. Moreover, documented requirements can be linked to the architectural elements of the system design to provide clear validation and verification linkages.[100]

Requirement validation and verification

The third main task of RE is the requirement validation and verification and it is a determinant step in all product development processes. Projects often tend to fail due to an inadequate or poor quality of their requirements. Validation refers to the concept of "doing the right things ", while verification stands for “doing things right”. Including this step for all products is crucial to detect and eliminate errors in the requirements.

For this reason, several quality criteria have been established to improve the quality of the formulation of requirements. The Project Management Institute formulates the characteristics that must be met in well written, good quality requirements.[101] The following characteristics can be differentiated:

- **Unambiguous**: The requirement has only one meaning and is interpreted in the exact same way by the target audience.
- **Consistent**: The requirement must not duplicate or contradict other requirements.
- **Complete**: The requirement must include all the necessary information needed to design, construct, and test the attribute.
- **Measurable**: Quantitative or numerical data that describes a property of the requirement through an analysis, test, or demonstration.
- **Feasible**: The requirement can be applied within the known limitations and capabilities of the environment.
- **Traceable**: Each requirement has its own identifier and can be tracked or monitored during the whole product life cycle.
- **Precise**: The requirement defines precisely what needs to be fulfilled.
- **Testable**: All requirements must be allowed to be tested.[102]

Requirement management

The last main task of RE is requirement management (RM) and it is a very important subtask of it. Requirement management guarantees that all documents and information on requirements are kept accessible and up to date. RM develops three tasks: change management of requirements, requirements traceability and version control of requirements.[103]

[99] Cf. Friedenthal et al. (2015), A Practical Guide to SysML, p. 309
[100] Cf. Eigner et al. (2014), Modellbasierte virtuelle Produktentwicklung, p. 63
[101] Cf. Project Management Institute (2016), Requirements management
[102] Cf. Project Management Institute (2016), Requirements management
[103] Cf. Partsch (2010), Requirements-Engineering systematisch, pp. 22–23

2.5 Industry 4.0

Digitization and smarter manufacturing process are the necessity of nowadays industry. Manufacturing industries are moving from mass production towards customized production. The rapid developments in manufacturing technologies and applications in industries help to increase productivity. The concept of Industry 4.0 describes the fourth industrial revolution, which is characterized as a completely new organizational and control level of the whole value chain of the product life cycle (PLC), and which is oriented to the more and more individualized requirements of the customers.[104] In this chapter the term of Industry 4.0 will be defined below in more detail and also the terms of Cyber-Physical Systems (CPS) and Internet of Things (IoT) that from part of this new industry concept.

2.5.1 Industry 4.0 introduction

Industry is the area of the economy that produces highly mechanized and automated material goods.[105] Ever since the first Industrial Revolution, further revolutions have given rise to manufacturing, from water and steam driven machines to automated electric and digital production. These recent advances make the manufacturing process more complicated on the one hand, but at the same time automatic and sustainable so that users can efficiently and consistently operate the machines.[106] As mentioned before, the concept of Industry 4.0 stands for the fourth industrial revolution and engages with a large range of concepts which include increases in digitalization, mechanization and automation, miniaturization, and networking.[107] The following figure shows how the industry has evolved and developed ever since its origins until the nowadays.

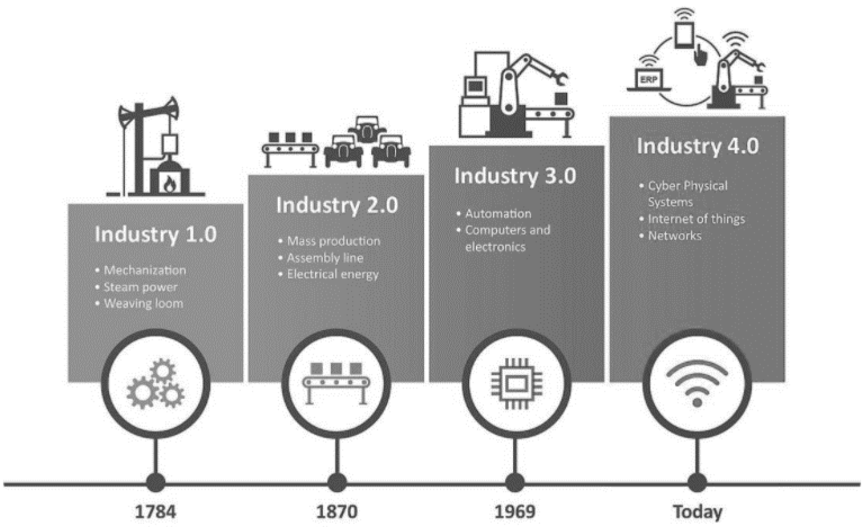

Figure 14: Evolution of the industry over the years.

[104] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 233
[105] Cf. Dr. Heiner Lasi & Prof. Dr. Hans-Georg Kemper (2014), Industry 4.0, p.239
[106] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 233
[107] Cf. Ceren Salkin, Industry 4.0: Managing the Digital Transformation, p. 23

The Industrial Revolution brought many improvements in manufacturing and service systems. Due to the significant and quick changes in manufacturing and information technology, there was a synergy resulting from the integration of advances in manufacturing processes, information technology and services. These advances led to productivity gains in services systems as well as in the manufacturing environment.[108]

Companies today are faced with the challenges of making quick decisions to increase productivity. An example could be the process of transformation towards automation of machines and services, leading to the connection and coordination of complex distributed systems.[109] To this end, more and more systems are embedded in the software of industrial products and systems, so prediction methods must be made up of intelligent algorithms in order to sustain the electronic infrastructure.[110]

According to BITKOM, VDMA, ZVEI'S report, there is an increase in the amount of physical elements that get receivers such as sensors and tags as a form of constructive technology. In addition, the connection of electronic devices is done as part of distributed systems to facilitate the accessibility of all relevant data in real time processing.[111] Furthermore, the possibility to derive patterns from the data at any instant allows more accurate prediction of system performance and enables an automatic control of the system.[112] All these developments are influencing today's industrial and manufacturing processes; therefore, the model of the Industry 4.0 has emerged in the recent years.

2.5.2 Industry 4.0 definition and main concepts

Industry 4.0, which is sometimes also referred to as IoT or smart manufacturing, brings together production and operations with big data analysis, machine learning and smart digital technology. This new innovative model provides a better connected and more holistic ecosystem for companies focused on supply chain management and manufacturing. The Industry 4.0 model drives the connection of physical components such as sensors, equipment and business assets, both with one another and with the Internet.[113]

The main objective of Industry 4.0 is to meet the individual needs of customers, which affects fields such as R&D, order management, delivery through to product usage and recycling of the product. Another challenge of Industry 4.0 is to turn normal machines into self-aware and self-learning machines to upgrade their operational performance and maintenance management with the interaction of the environment.[114]

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[108] Cf. Ceren Salkin, Industry 4.0: Managing the Digital Transformation, p. 22

[109] Cf. Ceren Salkin, Industry 4.0: Managing the Digital Transformation, p. 23

[110] Cf. Lee J et al. (2015), A cyber-physical systems architecture for Industry 4.0-based manufacturing systems, pp. 18-23

[111] Cf. Bitkom, VDMA, ZVEI (2016), Implementation strategy Industrie 4.0: report on the results of the Industrie 4.0 Platform

[112] Cf. Ceren Salkin, Industry 4.0: Managing the Digital Transformation, p. 23

[113] Cf. K Sipsas et al. (2016), Flow-line manufacturing environments: An Industry 4.0 approach, pp. 236-241

[114] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 234

Industry 4.0 has also the goal of building an open and intelligent manufacturing platform for the application of networked industrial information. Real-time data monitoring and tracking the position and status, as well as maintaining instructions to control manufacturing processes are the main requirements of Industry 4.0.[115]

In addition, the industry 4.0 concept includes technologies like cyber physical infrastructure, big data analysis, autonomous and adaptive robots, horizontal and vertical integration, simulation, Industrial internet and cloud systems, augmented reality and additive manufacturing.[116] All these technologies mentioned are needed to obtain a successful adaptation. *Figure 15* shown below, illustrates the architectural design of an Industry 4.0 model.

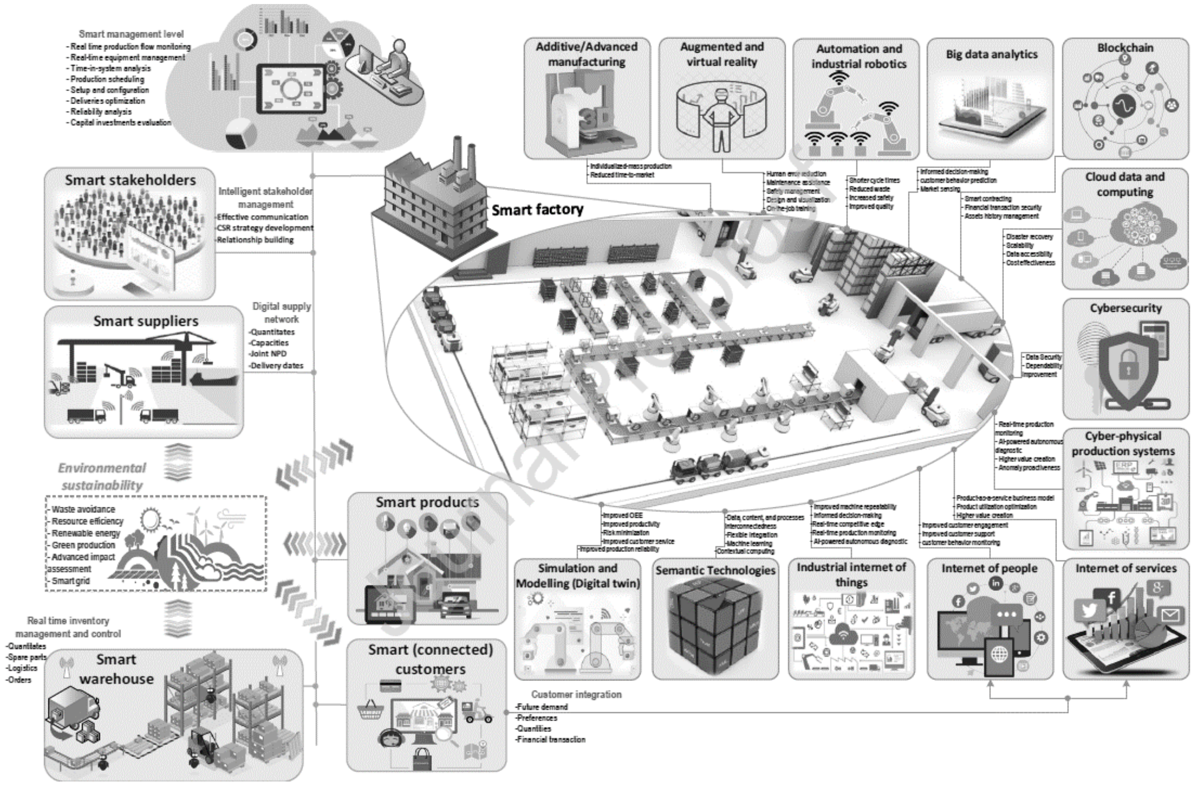

Figure 15: Industry 4.0 architectural design.[117]

There are nine basic pillars in the Industry 4.0 model that convert production from isolated cells to a fully integrated, automatized, and optimized production stream. This results in increased efficiency and a shift in the conventional production relationships between suppliers, manufacturers and customers, and also human-machine interaction.[118] *Table 2* shows the pillars mentioned and they are described in detail below.

[115] Cf. F. Almada-Lobo et al. (2015), The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES), pp. 16-21.

[116] Cf. Ceren Salkin, Industry 4.0: Managing the Digital Transformation, pp. 24-25

[117] Cf. Morteza Ghobakhloo et al. (2019), Industry 4.0, Digitization, and Opportunities for Sustainability, p. 9

[118] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 234

Pillars of the Industry 4.0 model		
Big Data and Analytics	System Integration	The Cloud
Autonomous Robots	The Industrial Internet of Things	Additive Manufacturing
Simulation	Cyber security and CPS	Augmented Reality

Table 2: Pillars of Industry 4.0.[119]

Big Data and Analytics

The comprehensive collection and evaluation of information from many different production equipment and systems sources, and from business and customer management systems will be essential to provide real time decision support.[120] WITKOWSKI divides Big data into four dimensions: variety of data, volume of data, value of data and velocity of generating new data.[121] The analysis of the recorded data is utilized to identify the hazards that happened in the previous production processes in the industry and also the forecasting of the new problems that occur as well as the possible solutions to prevent them from reoccurring in the industry.[122]

Autonomous Robots

Nowadays, robots are becoming more and more autonomous, collaborative, and flexible and in the future, they will be able to interact with each other and humans and learn from them.[123] An autonomous robot is designed to carry out the autonomous production method more accurately as well as to work in situations where human operators are limited in their work.[124] The table below shows four examples of these type of robots used in various industries.

Name of Robot	Company	Function of Robot
Kuka LBR iiwa	Kuka	Lightweight robot for sensitive industrial tasks
Baxter	Rethink Robotics	Interactive production robot for packaging purpose
BioRob Arm	Bionic robotics	Use in proximity with humans
Roberta	Gomtec	6-Axis industrial robot for flexible and efficient automation

Table 3: Autonomous robots used in industries.[125]

[119] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, pp. 234-237
[120] Cf. M. Rüßmann (2015), Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, p. 7
[121] Cf. K. Witkowski (2017), Industry 4.0- Innovative Solutions in Logistics and Supply Chains Management, p. 765
[122] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 234
[123] Cf. M. Rüßmann (2015), Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, p. 9
[124] Cf. MAK. Bahrin et al. (2016), Industry 4.0: A Review on Industrial Automation and Robotic (2016), p 137–143
[125] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 235

Simulation

Simulations are useful in plant operations to take advantage of real-time data and reflect the physical world in a virtual model, which can include products, machines, and workers, thus reducing machine set-up times and improving quality.[126] 2D and 3D simulations can be generated for virtual set-up and for simulating cycle times, energy consumption or even ergonomic aspects of a production plant. Using production process simulations can not only reduce changeovers and downtimes, but also minimize failures in production during the set-up phase.[127]

System Integration: Horizontal and Vertical System Integration

The two main mechanisms used in industrial organization are integration and self-optimization. In the Industry 4.0 there are three different dimensions of integration: horizontal integration, vertical integration, and end to end integration. Full digital integration and automation of production processes in the horizontal and vertical dimension also implies automation of the communication and cooperation, in particular across standardized production processes.[128] *Figure 16* bellow provides a brief overview of the mentioned system integration.

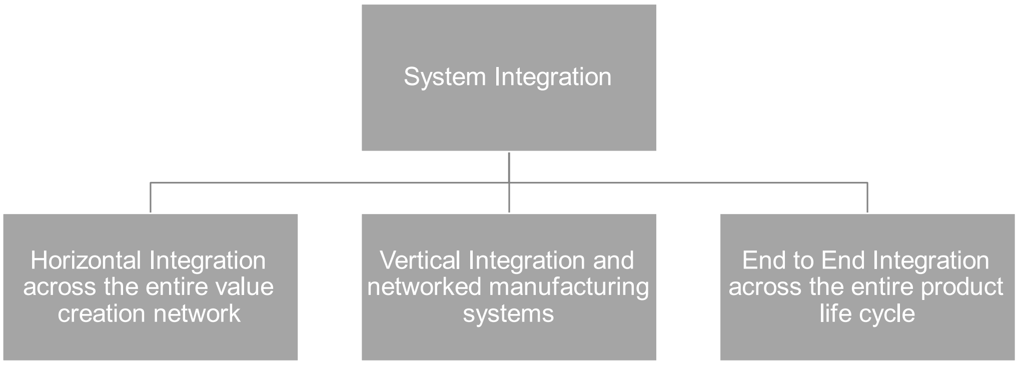

Figure 16: System Integration.[129]

The Industrial Internet of Things

The Internet of Things (IoT) stands for a global network of interconnected, uniformly addressed objects communicating through standard protocols. IoT makes possible the interaction of the objects (machines, products, robots, etc.) with the real-world environment and allow an immediate response to changes. It also provides information of the location or status of any object.[130] This concept of IoT will be described in more detail in this chapter.

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[126] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 235
[127] Cf. Simmons et al. (2017), Learning in the AutFab – the fully automated Industry 4.0, pp. 81-88
[128] Cf. G. Schuh (2014), Collaboration Mechanisms to increase Productivity in the Context of Industry 4.0, p. 51
[129] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 235
[130] Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, pp. 235-236

Cyber security and Cyber Physical Systems (CPS)

Industry 4.0 brings a growth in connectivity and the use of standards-based communication protocols, which need to be protected against cybersecurity threats. The cybersecurity implemented in the model will protect the whole industry system and the production lines form these new threats. Therefore, safe and reliable communications are essential, as well as the access management for both machines and workers and a sophisticated identification.[131]

In order to improve the quality of the data required for planning and optimizing manufacturing processes, it is essential to have a powerful connection between the physical and the digital world.[132] The term CPS describes a system where natural and man-made systems (physical space) are closely embedded with communication, computing and control systems (cyber space).[133]

The Cloud

The cloud-based IT platform represents the technical backbone for connecting and communicating the multiple elements of the Industry 4.0 Application Centre. With this new Industry 4.0 model, it is needed a high level of fast and optimized data sharing across the company and the environment.[134]

Additive Manufacturing

In the context of Industry 4.0, additive manufacturing methods will be used extensively to produce smaller batches of customized products that provide construction advantages, like complex and lightweight designs. Decentralized, high-performance additive manufacturing systems will shorten transport distances and reduce stock on hand.[135]

In addition, the decrease in product life cycles and the growth of customized product´s demand will produce an increase in complexity in manufacturing processes that can be solved with additive manufacturing.[136]

Augmented Reality

Systems based on augmented reality enable a multitude of services, including selecting parts from a warehouse and delivery of repair instructions via mobile devices. Augmented reality can be used in industry to provide real-time information to workers to improve work procedures and decision making. Workers can obtain repair instructions to replace a specific part while watching the real-time system in need of repair.[137]

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131 Cf. M. Rüßmann (2015), Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, p. 10
132 Cf. M. Landherr et al. (2016), Industry 4.0 - Industry-driven manufacturing, research and development, p. 27
133 Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 236
134 Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, p. 236
135 Cf. M. Rüßmann (2015), Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, p. 12
136 Cf. Saurabh Vaidya et al. (2018), Industry 4.0 – A Glimpse, pp. 236-237
137 Cf. M. Rüßmann (2015), Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, p. 14

2.5.3 Cyber-physical systems (CPS)

Cyber-physical systems (CPS) are systems of cooperating computational entities that are in strong connection with the external physical world and their current processes, at the same time providing and using data processing services that are available on the Internet.[138] CPS integrate sensors, computation, monitoring and networking across physical objects and infrastructure, connecting these to each other and to the internet. CPS are based on one hand on new and foreseeable developments in computer and information and communication technologies, and on the other hand in manufacturing engineering and technology.[139] As mentioned above they are one of the key pillars of the new Industry 4.0 model.

In addition, the term CPS relates to a new generation of systems with embedded physical and computational abilities that can interact with humans using many new approaches. The capacity to interact with the physical real world, with both machines and humans, and also augment its abilities through computation, communication and control is a crucial factor for the technological development of the future.[140]

The research aim of CPS is to integrate both knowledge and engineering principles along the computational and engineering fields, such as human interaction, networking, software, control, learning theory and other engineering disciplines, to further develop innovative supporting technology and CPS science. Nevertheless, the integration of several subsystems and yet maintaining the functional and operational system, proved to be time-consuming and very costly.[141]

There is a clear necessity to use CPS in production and manufacturing due to the increase in the complexity of the components, product customization, market competition and the shortening of the life cycles. Moreover, the price of sensors, multicore processors, and wireless communication, that used to be a big challenge for developing this new control and monitoring systems, have decreased drastically in the recent years. Therefore, CPS are set to play an important role in the development and design of tomorrow's engineered systems with advanced technologies that exceed significantly current functionality, autonomy, ease of use, cyber-security and reliability levels.[142]

CPS are made up of autonomous and coordinated elements and sub-systems that are connected to one another through all levels of production and logistical networks. These systems must solve the possible problems of having several operating sensors network, they need also to be able to handle big amounts of usage data and be able to interpret and represent this information. Another vital aspect that CPS needs to have a strong security so that the system is protected against cyber-attacks.[143]

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[138] Cf. László Monostori (2014), Cyber-physical production systems: Roots, expectations & R&D challenges, p. 9
[139] Cf. László Monostori (2014), Cyber-physical production systems: Roots, expectations & R&D challenges, p. 10
[140] Cf. Helen Gill et al., Cyber-physical Systems, p. 1
[141] Cf. Helen Gill et al., Cyber-physical Systems, p. 1
[142] Cf. Helen Gill et al., Cyber-physical Systems, p. 6
[143] Cf. Wayne Wolf (2009), Cyber-physical Systems, pp. 88-89

The key role of CPS is to allow and support the communication between machines, humans, and products. These systems are capable of acquiring and processing data, and specific activities and interact with humans through interfaces.[144] *Figure 17* illustrates the interaction between a human and a machine in a CPS.

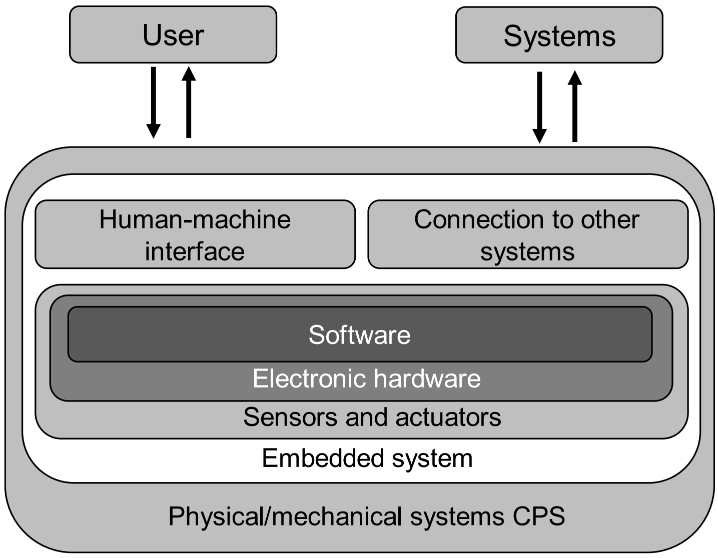

Figure 17: Interaction in CPS between humans and machines.[145]

The possible application fields are almost infinite from continuous and discrete production systems and logistics to smart cities they will contribute to improve the quality of life. In order to develop an efficient CPS, the following aspects must be considered:

- **Context-adaptative and autonomous systems**: Methods need to be developed for continuous context awareness and for recognising, analysing, and interpreting the plans and intentions of objects.
- **Cooperative production systems**: Effective algorithms are needed for cooperative learning and distributes detection.
- **Identification and prediction of dynamical systems**: There is a need to expand available identification and prediction methods that can be applied on dynamical systems.
- **Robust scheduling**: New achievements must be made in the management of production disruptions.
- **Fusion of real and virtual systems**: Development of structures and methods to support the interaction between real and virtual sub-systems to obtain an intelligent production system which can adapt to changes in an uncertain environment.
- **Human-machine symbiosis**: The creation of a geometric data framework is needed to merge assembly features and sensor measurements to adjust and compensate the changes that occur in the real environment.[146]

[144] Cf. László Monostori (2014), Cyber-physical production systems: Roots, expectations & R&D challenges, p. 10
[145] Cf. László Monostori (2014), Cyber-physical production systems: Roots, expectations & R&D challenges, p. 11
[146] Cf. László Monostori (2014), Cyber-physical production systems: Roots, expectations & R&D challenges, p. 12

2.5.4 Internet of things (IoT)

The Internet of Things (IoT) is a global and dynamic network infrastructure with the ability to configurate itself via interoperable and standard protocols of communication, where virtual and physical “things” have individual identities, virtual personalities and physical properties. Therefore, everything is integrated in a global information network.[147] In addition, the International Telecommunication Union (ITU) defines IoT as “a global infrastructure for the Information Society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies’’.[148] It can be seen as the future Internet evaluation that carries out machine-to-machine (M2M) learning and offers connectivity for machines, products and humans.[149]

The application areas of IoT technologies are numerous and diverse and they are spreading to almost all aspects of our daily lives. Among the most notable application fields are, for example, smart industry, here the development of connected, intelligent production systems and production facilities is commonly referred to as Industry 4.0.[150]

The Iot is a combination of digital and physical components that brings new products and opens new business models. Due to more efficient power management, communication, memory reliability and improvements in microprocessor technologies, it is possible to digitize key functions and features of industrial products. As a result, a variety of opportunities are emerging for companies to create incremental value in the IoT.[151] The number of devices connected to the Internet is increasing at a rapid rate, therefore companies have begun to implement many products and services based on the IoT. Connecting all these devices to a network and implementing them with sensors to obtain real time information, can lead to huge and surprising applications and services that can result in substantial professional, personal and economic benefits.[152]

In addition, IoT is composed of objects, communication infrastructure, sensors, processing, and computing units that can be located in the cloud or decision-making systems. The International Telecommunication Union (ITU) say that the IoT “will connect real-world objects in a sensory and intelligent way”.[153] *Figure 18* illustrates a simple IoT system which implements different types of services or applications.

[147] Cf. David Hudson, Value Propositions for the Internet of Things: Guidance for Entrepreneurs Selling to Enterprises, pp. 5-11

[148] ITU (2012), New ITU standards define the internet of things and provide the blueprints for its development

[149] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 1

[150] Cf. Felix Wortmann et al., Internet of Things: Technology and Value Added, p. 221

[151] Cf. Felix Wortmann et al., Internet of Things: Technology and Value Added, p. 222

[152] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 1

[153] ITU (2012), New ITU standards define the internet of things and provide the blueprints for its development

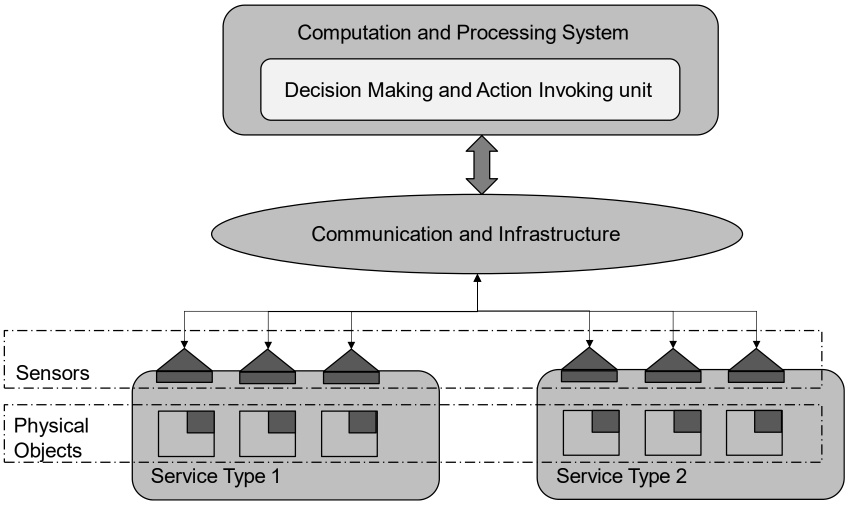

Figure 18: IoT basic system representation.[154]

In an IoT system, the “things” are connected and communicate with each other, and its basic workflow can be defined as follows:

1. The sensor implemented on the object collects the data about vibration, temperature, humidity, acceleration, etc. Different sensors can be used in combination for the development of smart products or services.
2. Triggering an action. The information received from the object is processed by an intelligent device or system which subsequently determines the automated action that needs to be done.
3. The system or device provides services that include mechanisms to report to the administrator feedback about the current states and the outcomes of the invoked actions.[155]

The IoT connects millions of different objects to each other creating larger traffic and needs a bigger data storage. Hence it faces many challenges especially concerning privacy and security. Therefore, the IoT architecture must deal with many factors such as scalability, quality of service or reliability. Moreover, its structure can be divided into five different layers as its seen in *Figure 19*.

[154] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 2

[155] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 2

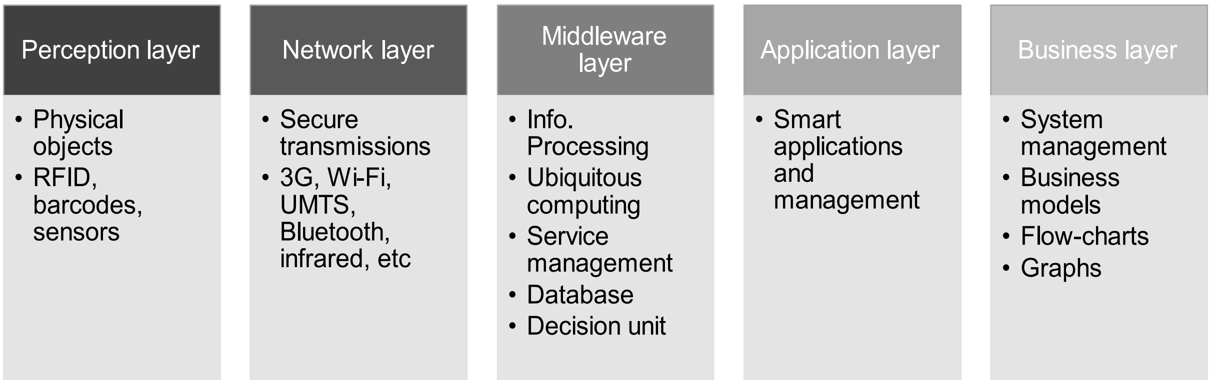

Figure 19: Architecture of an IoT.[156]

The different layers of the architecture of an IoT system showed in *Figure 19* are briefly detailed below:

- **Perception Layer**: This layer is formed by the physical objects and sensor devices. It is where the specific information is identified and collected by the sensors and then transmitted to the network layer.
- **Network Layer**: It transfers the information form the sensors to the information processing system. In other words, it is the bridge between the perception layer and the middleware layer.
- **Middleware Layer**: This layer oversees the service management and has a direct link to the database. Therefore, it stores in the database the information it receives from the network layer.
- **Application Layer**: It allows the management of the applications based on the information from the middleware layer.
- **Business Layer**: This layer is in charge of the entire IoT system management, including both applications and services. It creates business models, flowcharts, or graphs on the basis of received data from the application layer.[157]

To sum up, through a IoT system everything will be connected, and it will incorporate intelligence into sensor devices so that they can in an autonomous way communicate, exchange information, and make their own decisions. It will convert the human-to-human communication to a human-to-human, human-to-device, and device-to-device communication.[158]

[156] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 2

[157] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, pp. 2-3

[158] Cf. Khan, R. et. al. (2012), Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges, p. 5

2.6 Interim conclusion

In purpose of obtaining the theoretical background for the evaluation of existing approaches which are presented in the following chapter, the basic foundations for the range of topics that are most relevant for this thesis were given.

In Chapter 2.1, a common understanding of the whole product life cycle (PLC) is provided by defining each of the seven phases of itself from the concept creation until the product retirement.[159] Moreover, the term of product usage is referred to the phase when consumers are making use of the product after purchasing it. Also, product usage information (PUI) is defined as the knowledge extracted from the usage phase. By having a clear definition of the usage phase and PUI it is easier to understand how customers use the product, therefore next product generations can be improved. In the third section, Chapter 2.3, the product functions are described as relationships between an input and output of a system with the aim of fulfilling a specific task.[160] In the following section, it is stated that the objective of customer value is to describe, analyse and empirically evaluate the value that companies create for their customers.[161] Therefore, if the product functions are adjusted to what the customers really need and expect from a product, the next product generation will have a much higher customer value. In order to adjust the product functions to improve the product, it is of vital importance to analyse the requirements and subsequently to collect, document, evaluate and manage them as described in Chapter 2.4.

This process of collecting information from the usage phase to improve, adapt, or eliminate product functions so that customers requirements are met, and the product is improved, still requires a high manual effort. Thus, in Chapter 2.5 is seen how a product can be connected to a system and how the information can be transferred in real time through cyber-physical systems (CPS) or the Internet of things (IoT). In conclusion, it is crucial that products collect real time data through sensor devices and are connected to the internet to know how users manipulate the product, how their requirements change and how to constantly adapt the product functions to continuously improve next product generations.

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[159] Cf. Theresa Padilla (2018), Better product outcomes through key activities in the product life cycle

[160] Cf. M. Riesener et al. (2020), Modelling of Usage Hypothesis for the Identification of Innovation Potential, pp. 191-198

[161] Cf. Albert Graf and Peter Mass (2008), Customer value from a customer perspective, pp. 1-20

3 Existing Approaches

After discussing in Chapters 1 and 2 the motivation, background information and the problem statement of this research, Chapter 3 focuses on exposing existing approaches from previous research that uses product usage information to improve the next product generations. Furthermore, the examined approaches also identify which products attributes are more relevant for the users, to implement and improve these methodologies in machines, production lines and engineering plants. Firstly, the evaluation criteria for these methodologies or models are presented, then these criteria are compared to the approaches from the papers and literature reviewed and lastly, the research gap is clearly identified. The outcome of Chapter 3 will serve as the basis for developing the methodology of this work that will be described in the following chapters.

3.1 Evaluation criteria

In order to consistently evaluate the literature, including the scope and results of the research, it is important to define the evaluation criteria. In this case seven evaluation criteria are defined, and these are divided into object areas (O1-O4) and target areas (T1-T3).

Object areas (O1-O4) describe the context in which methodology takes place and they are defined below:

- **O1: Focus on developing machines and engineering plants:** The approach should focus on the development of machines and engineering plants to improve them and make them more efficient by analysing how they are being used in the usage phase.
- **O2: Use of product usage information (PUI):** The approach to be developed should focus on the use of PUI as the main source of information to improve next product generations. As already mentioned, the use of PUI to improve products or identify important requirements or attributes is increasing and becoming more relevant for companies but it is still an enormous potential that is not being fully exploited. Hence, this evaluation criteria assesses if the reviewed literature extracts information from the usage phase of the product.
- **O3: Adaptation of product functions based on usage information:** The developed approach should use the PUI to identify which product functions are being used, which can be improved or eliminated. Therefore, in the literature reviewed there should be an actual use of the information extracted from the usage phase to change and improve the product.
- **O4: Integration of sensors and other devices to collect real time data:** This criterion will evaluate how the data is being collected in the different research analysed. It is important that the data used to improve the next product generations is updated because customerrequirements and needs are constantly changing, hence real time data will allow the developers to adapt the product functions to these changing requirements.

Target areas (T1-T3) describe the goals or objectives which the methodology developed on this thesis is going to aim at. Therefore, the target areas described below will assess if they are addressed or implemented in the literature reviewed.

- **T1: Modelling of the usage phase:** This target criteria is considered in the methodology to be developed in this work because it is crucial to have the actual usage phase of the product clearly structured and represented so that product functions that must be improved or eliminated can be more easily identified.
- **T2: Filtration of requirements:** The methodology should detect which product functions are being used and how they are being used. With this information the requirements that the product should fulfil can be filtered and developed further.
- **T3: Variation of the product usage:** The methodology developed should also take into consideration how the product usage can vary when it is being used and how the user can influence the usage and thus the behavior of the product. The methodology should focus on gathering information on those aspects where the user can adjust the settings or characteristics of the functions. Hence, the functions that allow the user to influence the product performance during the product usage.

3.2 Evaluation approaches

This section explores the different approaches that exist in the literature. The extent to which these approaches match the resulting requirements of the target and object area of the previous chapter (see Chapter 3.1) will be assessed qualitatively. For every literature, the main results are highlighted and their suitability for the respective evaluation criteria defined is assessed. With this literature review, an overall comprehension of the present state of research is provided. The contributions relevant to this research are discussed below.

3.2.1 Object areas

In this sub-section it will be described in detail to which extend are the object areas mentioned in Chapter 3.1 fulfilled by the analysed literature. Moreover, this detailed description of how the object areas are satisfied will be used to develop *Table **5*** in Chapter 3.3 that serves as an overview of all the evaluation criteria.

O1: Focus on developing machines and engineering plants

One of the main aspects of this research is to focus on the use of PUI to improve next product generations in the field area of machines and engineering plants. As already mentioned in this work, more and more information is being obtained from the usage phase, due to several reasons like the decrease on the price of sensors and other measuring devices. With the PUI extracted from the usage phase companies are starting to use this data to improve all kind of products, but very few focus on the improvement of machines and plants. Two papers from ABRAMOVICI and another one from HARJA speak about how the information from the usage phase can be used to improve next generation of actual machines.

In the reviewed paper of MICHAEL ABRAMOVICI ET AL. (2011) the authors state that hydraulic systems are not operating at their highest efficiency.[162] Moreover, ABRAMOVICI says that “New ways of monitoring the product use provide opportunities to maintenance”.[163] This paper analyses the performance and possible damages of a centrifugal pump. In the analysed pump, there are several embedded sensors installed to record measurements regarding temperature, pressure, vibrations, and rotation speed. The data measurements were taken only once a day and if an incident happened was also recorded with its cause. The table below shows all the records that were taken.

Date	Time	ps	pp	ts	tp	te	s1	s2	fi	fd	Incident	Cause
25.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	237,5	237,5		
26.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	238,5	238,5		
27.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	229,0	229,0		
28.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	232,8	232,8		
29.09.07	10:00	1,39	3,25	18,47	43,34	25,12	7,00	5,81	235,5	235,5		
30.09.07	6:00	1,07	3,03	31,53	40,46	24,92	7,10	5,82	229,4	229,4	breakdown	bearing 1
30.09.08	7:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	232,8	232,8	cleared	
30.09.09	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	230,8	230,8		
01.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	230,0	230,0		
02.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	229,3	229,3	maintenance	
02.10.07	14:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	236,6	236,6		
03.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	231,0	231,0		
04.10.07	10:00	1,40	3,25	14,28	43,35	24,92	5,00	5,82	232,3	232,3		

Table 4: Excerpt from the Product Use Information.[164]

In the paper analysed from MICHAEL ABRAMOVICI ET AL. (2009) the authors present the use case scenario of a wire-electro discharge machine. In this paper ABRAMOVICI focuses on identifying the failures and breakdowns which occur more frequently and to subsequently reduce them to improve the following products generations. The coherence among rotary spindle sensor data (rotational speed), maintenance incidents over time (last maintenance) and failures of individual rotary spindle elements (drive belt breakage) from the usage phase can determine the areas or functions where the product must be improved.[165]

The third paper that focuses on the improvement of machines is the paper from HARJA. The focus of the research is the development of a universal CNC machine monitoring system to obtain real time data on the use of CNC machine tool components by clustering components according to their stage of operation so that it can be used in different types of CNC machine controllers. The paper presents four research stages: First it determines the machine utilization status, then there is an identification of the component pin which indicates each machine utilization status, the development of the machine monitoring interface and finally it conducts an experiment on a case study.[166]

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[162] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 1

[163] Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 1

[164] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 6

[165] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 235

[166] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, pp. 2-5

O2: Use of product usage information (PUI)

Usage information can play an important role for companies when they want to improve their products in order to adapt to the changes in the market and satisfy in customer´s requirements. Lots of companies from different sectors or markets know that and are starting to obtain PUI from the usage phase. OLSSON says in her approach that there are lots of opportunities to learn about the real usage of a product, to inform product management decisions and to keep on improving products already deployed.[167] In her study she analyses three different companies and although the three of them extract data from the usage phase only one of the three uses it to improve next product generations.[168] Therefore, companies are starting to realize that PUI has an enormous potential but still there is a long journey to be done until they fully exploit it to keep on upgrading product next generations.

The other reviewed literature for this work focuses more on how they collect and use the PUI to analyse the real usage of the product and subsequently using it to improve the product itself. For example, SUK JIN develops a continuous usage model for the adoption and continuous use of a smartphone. He starts by dividing the attributes or characteristic of the product in three main different factors:

- **Product quality factors**: They represent the perceived ease of use and usefulness.
- **Sociocultural factors**: Social factors associated with image, subjective norms and visibility affect the usability and ease of use. Cultural factors are set of believes, traditions, language, moral values, and laws of a defined group of people.
- **Continuous usage factors**: They depend on the user's attachment and satisfaction and commitment to continue using the product.[169]

SUK JIN, after developing the continuous usage model carries out surveys and subsequently he performs a statistical analysis of this surveys. To prove the reliability of the measurements obtained from the information of the surveys, he analyses de Cronbach´s alpha value excluding the latent variables with a value lower to 0,7.[170] *Figure 20Figure **20*** shows how the factors mentioned, in a higher or lower way, affect consumers on continuing using the product. Unfortunately, the approach developed by SUK JIN does not focus on improving specific product functions or fulfilling customer requirements on the product. It rather focuses on generic factors that can influence a consumer's intention to continue using the product. Moreover, the PUI data obtained is derived from conducted surveys hence it cannot be considered real time data.

[167] Cf. Helena Holmström Olsson et al. (2013), Towards Data-Driven Product Development: A Multiple Case Study on Post-Deployment Data Usage in Software-Intensive Embedded Systems, p. 2

[168] Cf. Helena Holmström Olsson et al. (2013), Towards Data-Driven Product Development: A Multiple Case Study on Post-Deployment Data Usage in Software-Intensive Embedded Systems, pp. 6-10

[169] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, pp. 566-568

[170] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, pp. 570.

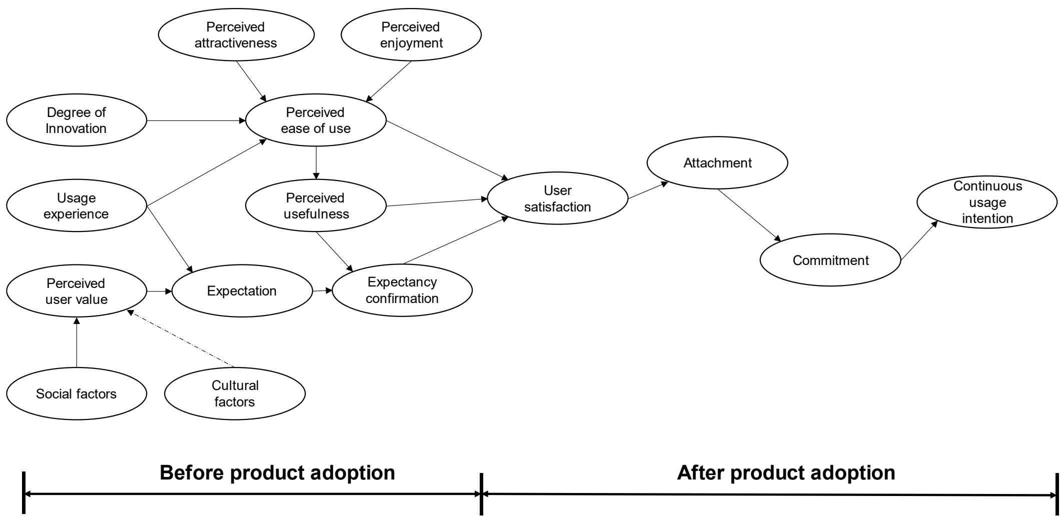

Figure 20: Continuous usage model after results.[171]

According to the reviewed paper from HARJA, in his approach, first it was determined the actual usage phase of the machine, then the component pin of the machine usage phase was identified and after that it was developed a machine monitoring interface.[172] The machine monitoring system consists of two interfaces: the hardware interface and the graphical user interface that is the software application. The hardware monitoring unit is constructed using a microcontroller and various relays which can be shown in the schematic diagram of the monitoring unit (*Figure 21*) and in the circuit of the microcontroller algorithm (*Figure 22*).[173]

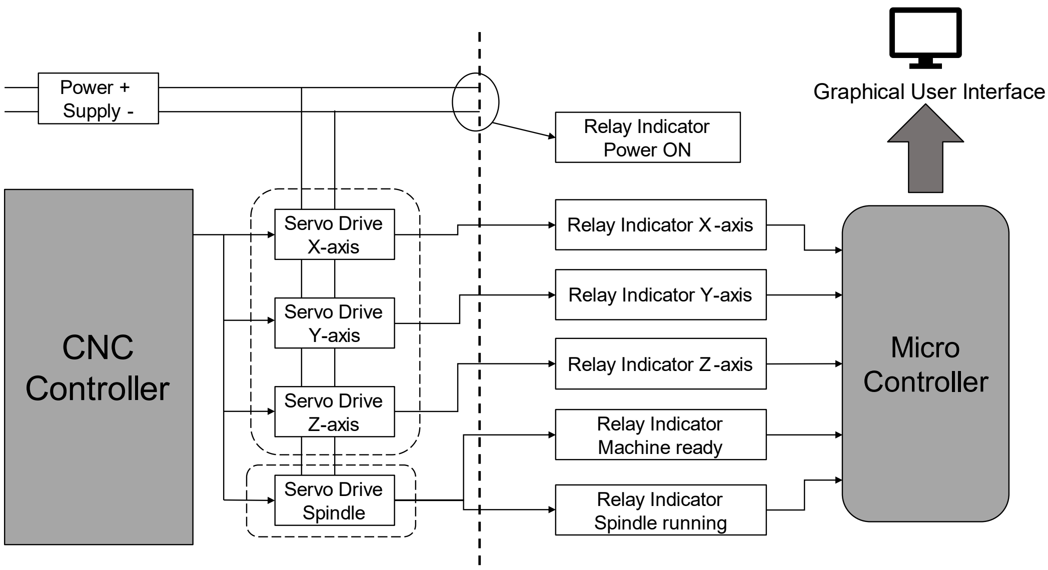

Figure 21: Monitoring unit schematic.[174]

171 Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, p. 578

172 Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 3

173 Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, pp. 5-6

174 Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 4

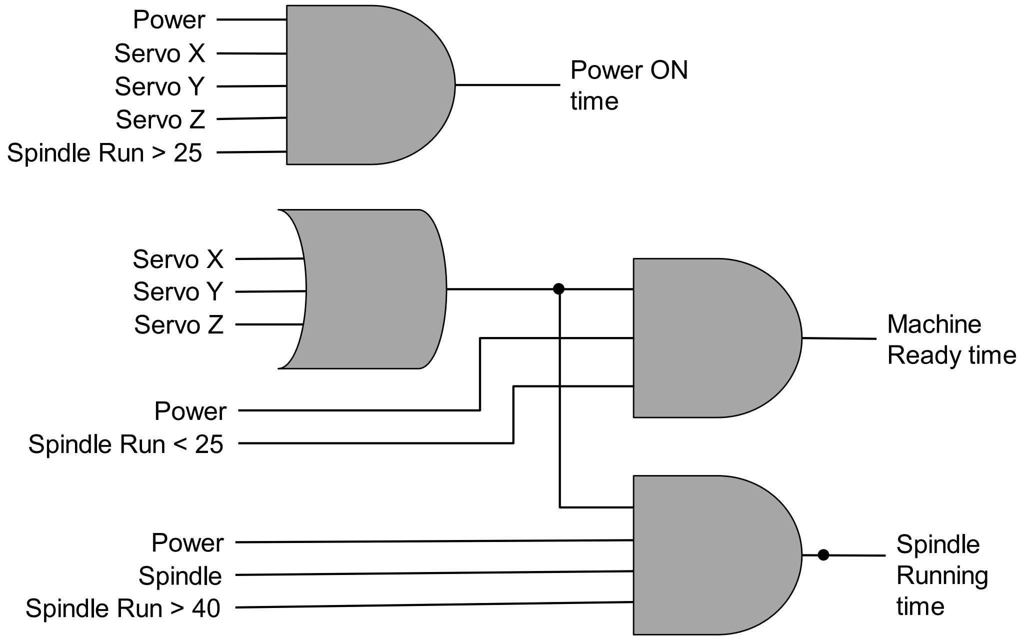

Figure 22: Microcontroller algorithm circuit schematic.[175]

The monitoring system of this paper is capable of displaying information about the status of the operating phase, including the duration time, and displaying this information through an interface.[176] This approach could also involve other machine operations in the future so enough data can be obtained from different product functions.

The approach presented by KLEIN proposes to use a 'virtual open platform' (VOP) to collect and process all the data generated. To collect the data, sensors were implemented in a washing machine, which was the case study in his paper. With these sensors about 40 different data streams were collected in addition to 40 status variables obtained from the control unit embedded in the machine.[177] KLEIN also developed a workflow for the analytics of the PUI collected as represented in *Figure 23*.

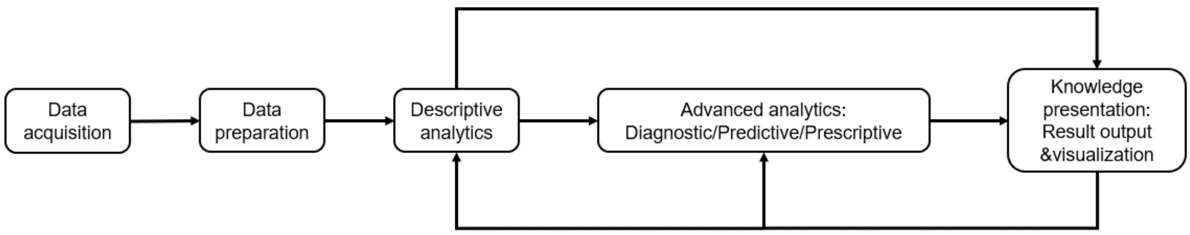

Figure 23: Workflow for the analytics of the PUI.[178]

[175] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 5

[176] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 7

[177] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, pp. 2630-2632

[178] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, p. 2629

The first step collects the PUI data with the implemented sensors and control unit mentioned above. After that, the collected data must be prepared before it can be used in the next steps of the workflow. The next step is the descriptive analytics that normally consists of a combination of data wrangling and querying. The output of the data analytics are tables and visualizations that enable the user to select the advanced analysis tools that are needed for the next iteration, to set their parameters and to adapt the set of descriptive analysis and wrangling operations. After the descriptive analytics proceeds the advanced analytics where diagnostics are applied to identify trends and patterns, predictions are achieved through machine learning and simulations and the perspective analytics recommends which actions must be taken.[179] Finally, after going through all the stages of the workflow the knowledge extracted can be used to improve next product generations.

In the research KLEIN uses the 'FALCON' as a VOP to run the descriptive analytics because it mainly focusses on aggregation and filtering.[180] It is a tool which enables the collection and processing of data generated by connected products and social media, with the aim of extracting actionable knowledge to be utilised as an input for the (re)design of related products. *Figure 24* illustrates the simplified architecture of the VOP presented.

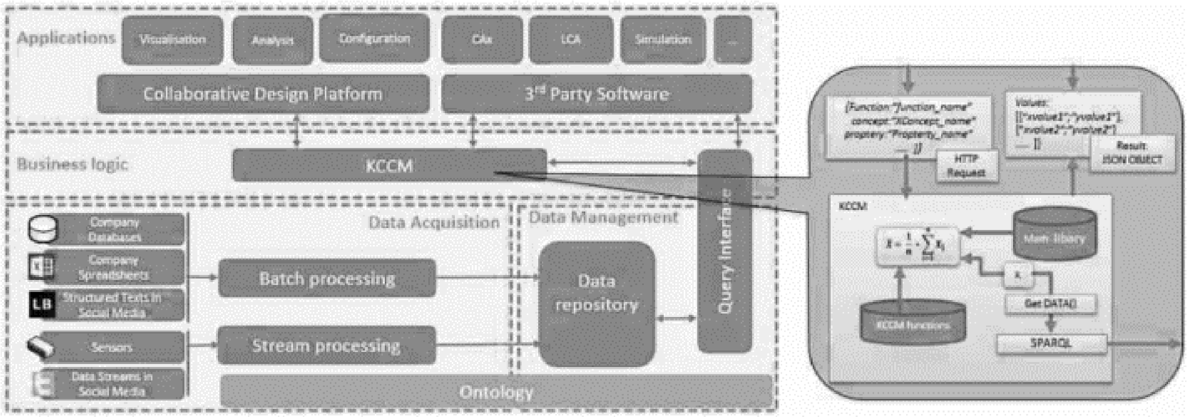

Figure 24: Simplified architecture of the FALCON VOP.[181]

The lowest level of the FALCON architecture supplies modules for data access and data acquisition. Multiple acquisition modules link the platform to different sources of PUI. Batch processing enables the connection to sources which include the database of the company, structured documents, semi-structured texts, and e-commerce backends. Usage data is organised and made interoperable across the VOP through an ontology, which is a fundamental information model for the entire platform. All platform operations can be conducted with the assistance of the ontology and its description logic.

[179] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, p. 2629

[180] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, pp. 2630-2632

[181] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, pp. 2630-2632

Another important layer of the architecture is the business logic layer, were the Knowledge Consolidation & Cross sectoral Management module (KCCM) provides functions for the transformation and filtering of accessed data and statistical counting operations. In the layer above the business layer, the data be used in applications through collaborative design platforms or 3rd party software.[182]

In the literature reviewed from LÜTZENBERGER the author states that PUI such as user feedback or sensor data becomes a key factor for future product development success. In his approach he addresses that there is a shortage of research for a systematic transference of PUI obtained into product design requirements. He proposes that a KbeML system, which is a formal extension of the established modelling languages SysML and UML, allowing a linking of PUI and KBE formalised models. In addition, KbeML enable on the one hand a formal and objective representation of usage data and on the other the representation of design knowledge.[183] The following Venn diagram illustrates the relationship illustrates the relationship between KbeML, SysML and UML.

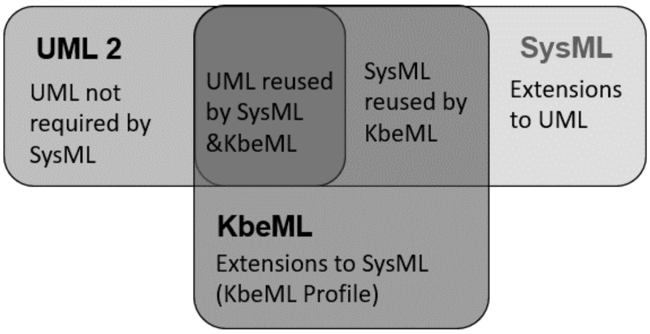

Figure 25: Relationship between KbeML, SysML and UML.[184]

LÜTZENBERGER´S approach monitors the bearing lifetime of a washing machine to try to see how the usage of the washing machine affects the lifetime of this component so a more appropriate one can be selected or designed to improve the product. To do so, first the centrifugal force that acts on the machine needs to be calculated by the means of PUI parameter (information obtained from the sensors) and CAD parameter (design parameters). The sensors on the machine obtain the load mass, the number of spins and the unbalanced load measure. The diameter of the drum, which is a CAD parameter, is also needed. After that, an arithmetic mean is applied to all centrifugal force measurements so that the forces acting on the bearing can be determined to subsequently determine the bearing lifetime.[185] The figure below represents a simple schema of the approach presented by LÜTZENBERGER.

182 Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, pp. 2630-2632

183 Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, pp. 376-377

184 Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, p. 377

185 Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, pp. 378-381

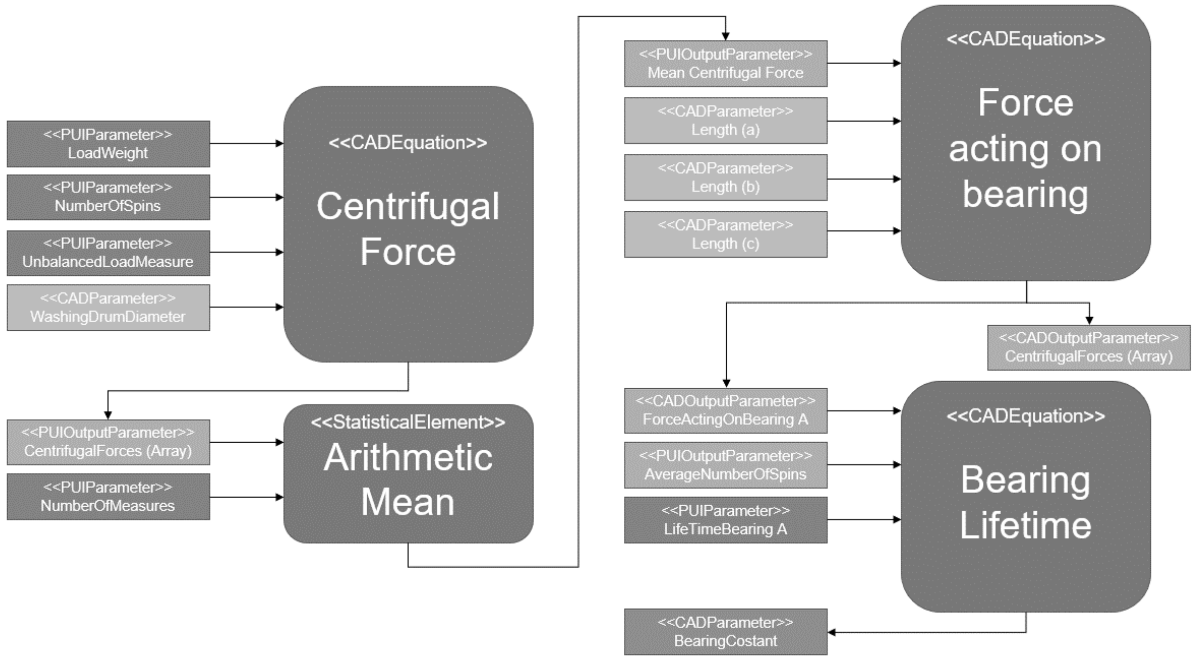

Figure 26: Schema for the Bearing Lifetime calculation based in PUI.[186].

With this approach, the PUI obtained from the sensors embedded in the machine can be used to adapt the product to needs of customers and services can be created. The overall lifetime the components monitored can be increased and adapted to the functions more demanded by customers.

In the first paper reviewed from MICHAEL ABRAMOVICI ET AL. (2011), he presents an approach for transferring feedback from usage information into product development to improve future product generations. Furthermore, the research describes the diagnosis and analysis of PUI by an implemented assistance system prototype.[187] The PUI considered for this approach is divided into the following groups:

- **Sensor data of the machine**: Data obtained from sensors during the usage of the machine, such as the following:
    - Operational parameters: temperature, rotation speed, oscillation, etc.
    - Resource consumption: energy, material, etc.
    - Use incidents: breakdowns, failures, etc.
- **Sensor data of the environment**: All the data that directly affects the machine environment and has a direct impact on the operations performed.
    - Operational environment: Room temperature, pressure, or humidity.
    - Workspace information: influencing neighbour components or parent assembly.
- **Data generated by service staff**: Data collected during the service activities such as, maintenance or replacement of components.

[186] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study. p. 380

[187] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 1

- **Data about the service staff**: Data regarding the service staff like personnel data, qualification, or workload.
- **Quality parameters**: Data that can be produced in an automated way or through staff and refers to the quality of the production.[188]

During the use of multiple instances of product generation m, the PUI is produced and saved in several heterogeneous databases (*Figure 27*), which are either customer implemented or are part of existing commercial software systems such as ERP or CRM-system. The approach uses one central data base to collect and store all the information obtained during the product use of all product instances. Therefore, it states that a known and open data format must be used because the system can vary depending on the customer. Once the analysis and diagnostic methods have been applied by the "Feedback Assistant System", the results are provided to the product developer in an easy-to-use user interface.[189]

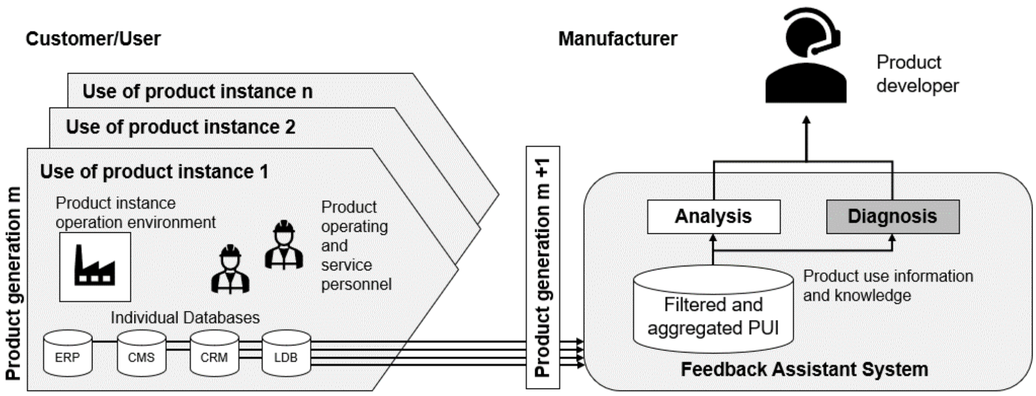

Figure 27: Schema of the feedback assistance system.[190]

As shown in the figure above, there are two different modules in the "Feedback Assistant System", the analysis module and the diagnosis module. The analysis module helps the product developer to analyse the requirements specification of product generation *m* in order to define, for the requirements specification of product generation *m+1*, whether all requirements are still fulfilled, whether new requirements need to be added or whether further improvements are necessary. The second module, the diagnosis module helps to decide how the following product generation *m+1* improvements can be performed according to the requirements.[191] ABRAMOVICI uses What If Analysis to perform the diagnosis module and they consist of Bayesian networks. These networks represent causal or probabilistic network and they are suitable for representing uncertain knowledge and possible resulting conclusions.[192]

[188] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 2

[189] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, pp. 3-4

[190] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 2

[191] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 7

[192] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 234

Figure 28 and *Figure 29* represent the analysis module and diagnosis module, respectively, that were carried out in this examined paper.

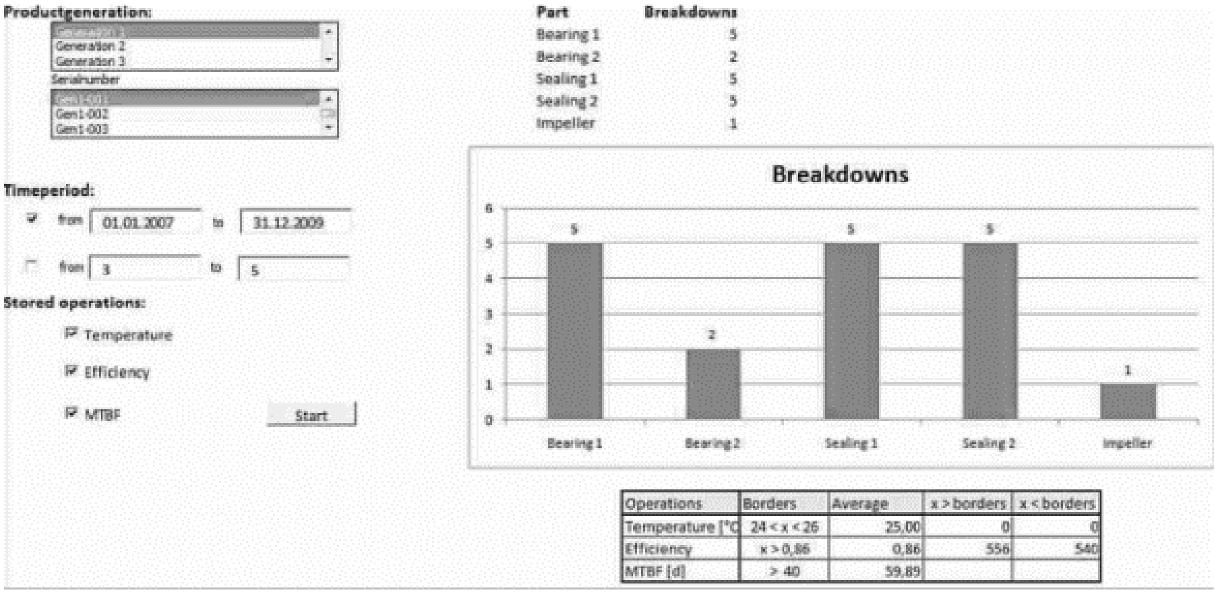

Figure 28: Graphical interface of the analysis module.[193]

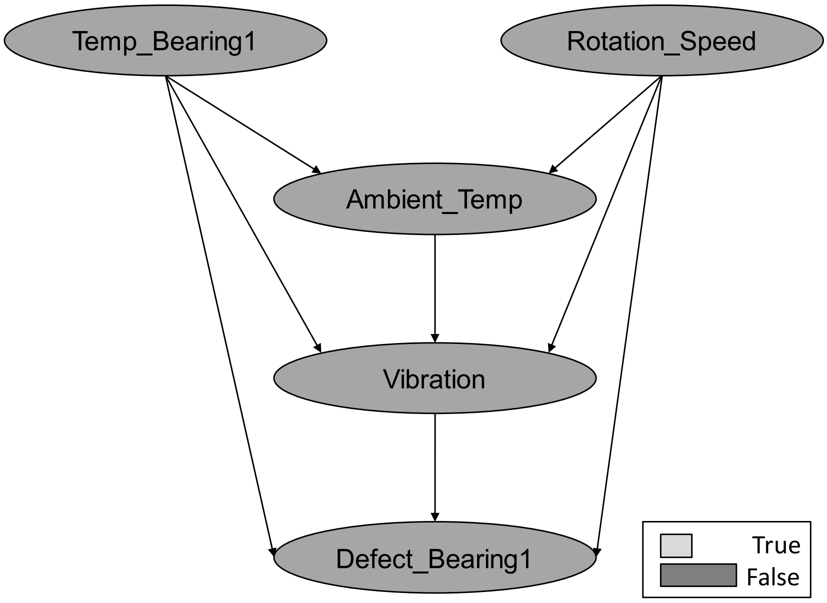

Figure 29: What if analysis represented by a Bayesian network (Diagnosis module).[194]

193 Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 7

194 Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 8

The paper from MICHAEL ABRAMOVICI ET AL. (2009) presents a similar approach for the transfer of PUI into product development. The following figure provides an overview of the solution presented.

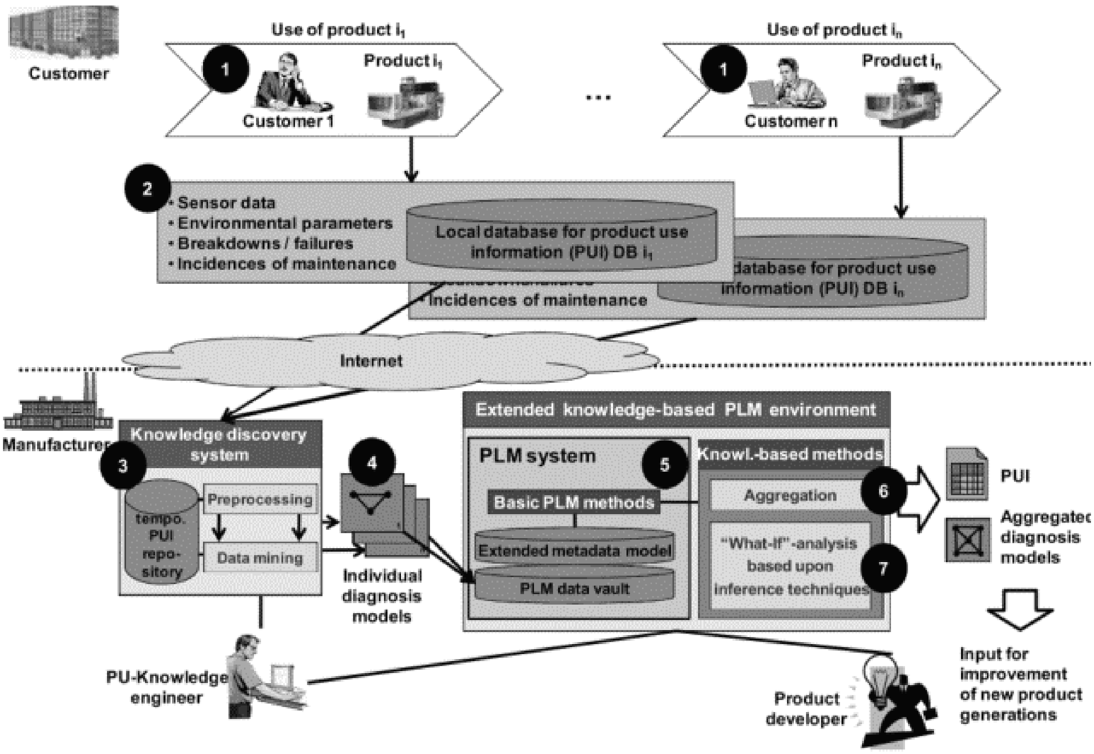

Figure 30: Overview solution of the feedback PUI into product development.[195]

In the upper half of the figure illustrates the situation during the use phase of the product for multiple customers. Every customer can use the product in a different environment and load scenarios (1). The data collected is then collected in local databases, this PUI is based, like in his other approach mentioned above, in sensor data, environmental parameters, breakdowns and failures, and incidences of maintenance (2). These local data bases are connected to the internet, where the data can be transferred to a knowledge discovery system (3) of the manufacturer and with the help of an engineer individual diagnosis models are developed (4). Then the information is transferred to the PLM system (5) where knowledge-based methods are applied, like aggregation and "What-If" analysis (6). With the obtained PUI aggregation diagnosis are then developed and input information can then be used for the improvement of new product generations (7).[196]

Like in the other reviewed paper from ABRAMOVICI, he uses Bayesian networks for the modelling of product use knowledge. Bayesian networks consist of directed acyclic graph (DAG) in where the nodes represent random-variable incidences, and the directed edges stand for conditional dependencies. Each node receives a conditional probability distribution of the random variable it stands for. If additional critical values emerge, updated probability

[195] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 228

[196] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 228-229

distributions of these new random variables can be obtained via dedicated nodes in the Bayesian network.[197] The figure below represents some random variables that can cause a specific failure called “crack of drive belt” in the machine.

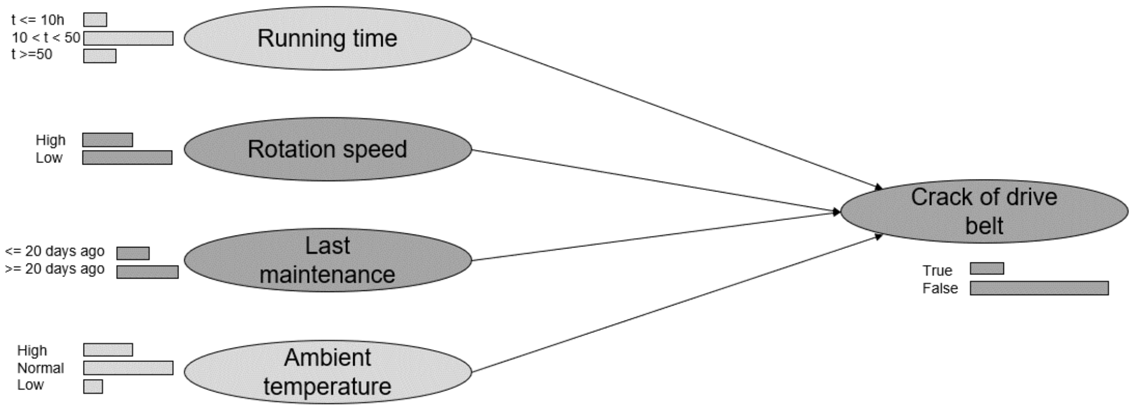

Figure 31: Failure "crack of drive belt" caused by influencing random variables.[198]

O3: Adaptation of product functions based on usage information

One of the objectives areas to be analysed is to see if the actual PUI is being used to adapt the product functions in order to improve the following products that will be developed. From the approaches of the literature that have been already mentioned not all of them make emphasis on using the collected data from the usage phase for developing next product generations. But the papers presented in this section speak about how the product functions can be adapted in future products to satisfy better customer needs.

LÜTZENBERGER speaks in his approach about how can both sensor data and user feedback form a washing machine be used to adapt the product to the actual needs of consumers. His methodology focuses on a continuous monitoring which will allow to adapt the programs of the product to the user’s usage and increase the lifetime of the washing machines.[199]

In the paper from MICHAEL ABRAMOVICI ET AL. (2011) the feedback assistance system developed focuses on two main tasks to improve new product generations. The system first supports the developer by identifying weak points of the parent product generation. The weak points of a product generation refer to frequently breakdown of product components and to functions that do not need to be met anymore due a change in customer requirements. The identification of these weak points is performed in the analysis module. The second task of the system is to identify appropriate actions to eliminate or mitigate the weak points to improve and adapt the product functions of the next product generations. These improvement actions are proposed in the diagnosis module.[200]

[197] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 234

[198] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 225

[199] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study. p. 380

[200] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 6

The second paper analysed in detail from MICHAEL ABRAMOVICI ET AL. (2009) also focuses in adapting the functions of the product in accordance with the information obtained from the usage phase. In this case the approach centres on the failures or breakdowns that occur more commonly when different users are using the same product functions in a different manner. The presented approach conducts detailed analysis on which factors influence or produce a specific breakdown. The information obtained about the impact that these factors have in the product functions is subsequently used to deduce improvement potentials to be done in the developing phase for future products.[201]

O4: Integration of sensors and other devices to collect real time data

The last object area to be observed is whether the information used in the approaches or models examined is real time data that comes from sensors integrated in the product or just feedback data from consumers that needs to be collected manually. SUK JIN obtains the PUI from surveys which are targeted to the paper´s use case product, hence the data obtained cannot be considered real time data and the whole process of data collection is not fully automated.[202] MICHAEL ABRAMOVICI ET AL. (2011) uses embedded sensors equipped in different parts of the centrifugal pump to take real time measurements regarding temperature, pressure, rotating speed, and vibrations.[203] Furthermore, LÜTZENBERGER considers in his approach to obtain real time information, sensors, PEIDS, IT components and social media (forums, blogs, helpdesks).[204] The rest of the literature reviewed in this chapter make use also of sensors integrated in the products to collect the data from the usage phase.

3.2.2 Target areas

This sub-section outlines in detail to what level the target areas described in Chapter 3.1 are fulfilled by the literature examined. Additionally, this detailed description serves as the base for the development of the methodology to be done in this work.

T1: Modelling of the usage phase

The first target area considered in this thesis is the modelling of the usage phase. This target area is vital for the methodology developed in Chapter 4 because it serves to understand in a structure manner the usage phase of the product. Of the seven papers reviewed in this chapter only two of them describe a simple model or structure of the usage phase.

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[201] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, pp. 227-229

[202] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, pp. 569-570

[203] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, pp. 5-6

[204] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, p. 377

In the reviewed paper of SUK JIN, he divides his usage model into two different phases: before adoption and after adoption. For in each phase, the relationship between user characteristics, socio-cultural, factors product quality, and continuous use factors was explored. The factors assigned to "before adoption phase" were associated with the product purchase and acceptance, while the factors assigned to "after adoption phase" corresponded to the usage of the product. The product adoption phase was further divided into orientation, incorporation (stimulation) and identification in order to assess changes in user satisfaction, attachment, commitment, and continuous usage factors as a function of the product usage experience.[205] The following figure illustrates the proposed model by SUK JIN for the continuous usage modelling.

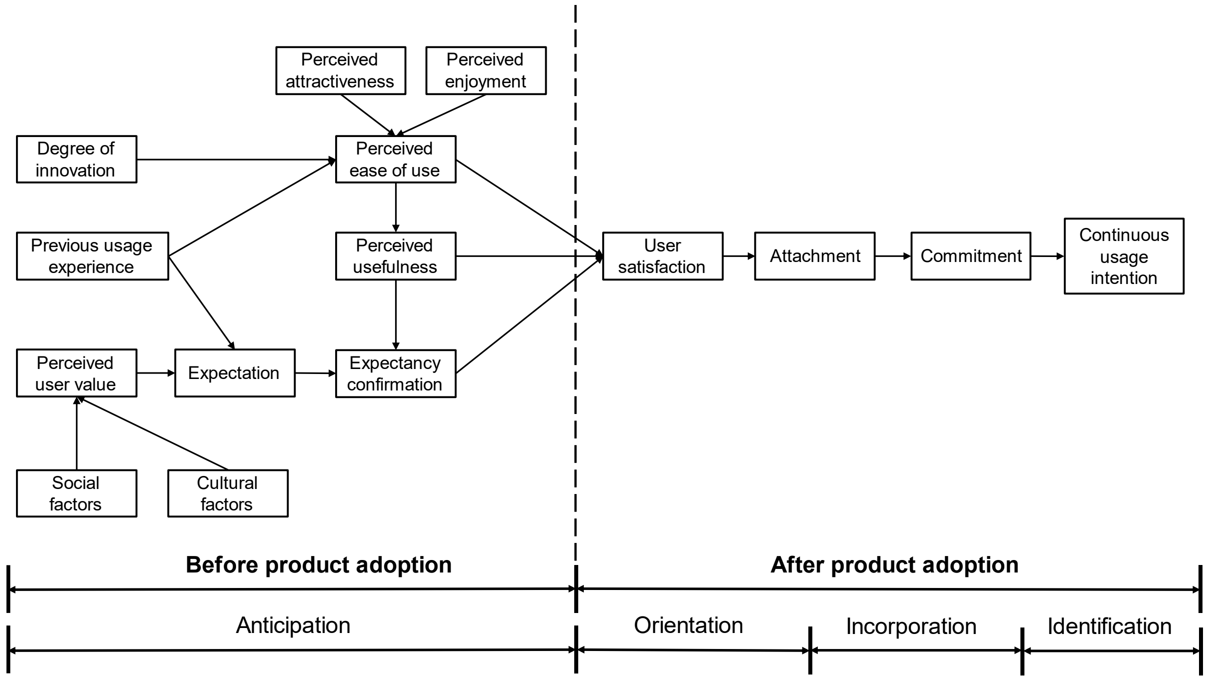

Figure 32: Continuous usage model.[206]

In addition, in the paper from HARJA, the author models the usage phase to identify the machine utilization status. In the case of this paper the usage phase was divided into three phases as the Venn diagram below shows: the power on phase, machine ready phase and spindle running phase. The power-on phase is the state in which the machine's power switch is turned on. The second phase, the machine ready phase is the state in which the machine's actuator system is ready to run commands. The spindle running phase is where the spindle component of the machine is rotating to perform the operations.[207]

[205] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, pp. 568-569

[206] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone, p. 569

[207] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 3

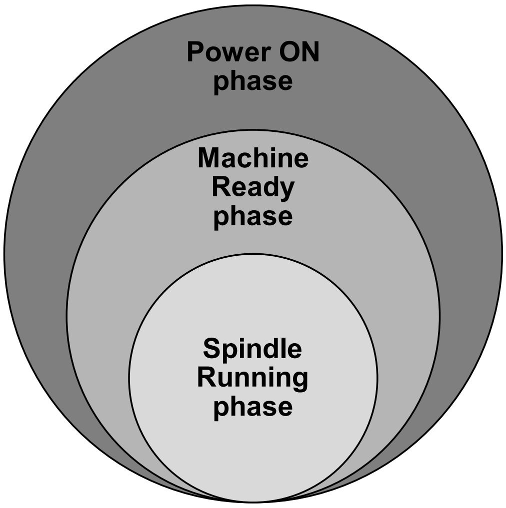

Figure 33: Machine usage status (Venn diagram).[208]

T2: Filtration of requirements

One of the important aspects of the methodology presented on next chapter is that it is crucial to focus on one hand on the most relevant requirements that the product must met but also on those requirements for the product functions that can vary the performance during the product usage. Moreover, these requirements must be linked to specific product functions that are able to fulfil them.

In the approach presented by KLEIN after obtaining the information from the sensors and other monitoring devices there is a stage of data preparation where there is a filtering of the data collected before it is transferred to the next stage.[209] Moreover, LÜTZENBERGER applies to the obtained data from the usage phase the arithmetic mean to calculate an average value of all value ranges so anomalous measurements can be mitigated. With the arithmetic mean the track of usage data can be transformed into a single value.[210] In the paper analysed from MICHAEL ABRAMOVICI ET AL. (2011) the feedback system created helps the developer find some weak points of the parent generation. These weak points are the product attributes or functions which are not important for the customer hence they can be eliminated or changed on oner hand, and functions that do not fulfil customer´s requirements on the other. Therefore, this identification of the weak points of the parent product can be considered a filtration of the requirements on the product because the presented approach focuses on the improvement of these weak points for the subsequent improvement of future product generations.[211]

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[208] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 3

[209] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development, p. 2629

[210] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, p. 378

[211] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 6

T3: Variation of the product usage

The last target area considered is the variation of the product use which refers to how can users vary the performance of the product by adjusting the settings or characteristics of the product functions.

Both papers from ABRAMOVICI use “What-If” analysis to analyse different scenarios and to evaluate their impacts on relevant variables in order to help the product developer in identifying potentials for improvement. Throughout this analysis it is easier to identify the components that most frequently breakdown, discover factors such as specific scenarios which have more influence on failures. In addition, the quantitative dependencies based on the product use information obtained in different usage scenarios under different conditions can be deduced.[212]

3.3 Interim conclusion

The literature review conducted in the previous chapter (Chapter 3.2), based on the definitions of object area and target area proposed in Chapter 3.1, has served to determine the current research gap in the use of PUI for the continuous improvement of the next generation of products. Moreover, this analysis enables the development of the methodology that will help to exploit the information from the usage phase in machinery and plant engineering and make use of it for the validation of assumptions for future products development. A summary of the literature analysis is provided below in *Table 5*.

The papers examined focus mainly on how to extract information from the usage phase of a product and how to use this information for the improvement of the product's functions in order to meet customer´s requirements and consequently improve the product itself. In the work of OLSSON, although she does not talk about any concrete method on how to use PUI to analyse or improve the product, it helps to understand the enormous potential that exists in this field and how companies are trying to take advantage of it and start using this information in the development of the next generation of products.[213]

The approach from HARJA is used in the same context of this thesis regarding the improvement in the development of machinery as it tries to analyse the real usage of a CNC machine. Another important aspect of this paper is that the usage phase of the machine is modelled, and it is one of the target areas of this work. Although his work tries to analyse the usage phase of the machine it only focuses on one product function of a specific product. hence his approach cannot be fully used for the development of the methodology of this work, but it can be taken into consideration.[214] The presented methodology by SUK JIN cannot be considered because all the information used from the usage phase comes from user’s surveys therefore there is a delay between the usage of the product and when is the information available.

[212] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development, p. 237

[213] Cf. Helena Holmström Olsson et al. (2013), Towards Data-Driven Product Development: A Multiple Case Study on Post-Deployment Data Usage in Software-Intensive Embedded Systems

[214] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250

In addition, his approach focuses on the improvement of the product in terms of the perceived value, attractiveness, and enjoyment that customers may have on a product, not on the improvement of product functions that satisfy in a higher degree their needs and requirements.[215]

In contrast, both works presented by KLEIN and LÜTZENBERGER use sensors to take PUI out of the usage phase of the product. Their approaches focus on detecting problems in product functions that do not meet user requirements or give rise to errors due to malfunctioning or broken components.[216] [217] Furthermore, LÜTZENBERGER uses in his approach the FALCON tool as a VOP for obtaining data on products that are connected to each other.[218]

As far as both models of the ABRAMOVICI papers are concerned, it could be concluded that they are closer to the objective of the methodology we intend to develop in this work. This is because they obtain PUI from the use phase by means of sensors implemented in the products, filter and analyse the "weakest" product functions and use all this information for the improvement of the next generation of products. Furthermore, they consider different scenarios and usage modes of product functions in order to better understand product performance and consumer requirements.[219] [220]

	Object area				Target area		
Literature	Focus on machines and engineering plants	Use of PUI	Adaptation of product functions	Extraction of real time data	Modelling of the usage phase	Filtration of requirements	Variation of product usage
BEOM SUK JIN ET AL. (2013)	○	●	◔	○	◕	◔	◔
HERMAN BUDI HARJA ET AL. (2018)	◑	◕	◔	◑	◑	○	○
PATRICK KLEIN ET AL. (2019)	○	●	◑	◑	○	◑	◑
JOHANNES LÜTZENBERGER ET AL. (2016)	◔	●	◕	◕	○	◑	◑
HELENA HOLMSTRÖM OLSSON ET AL. (2013)	○	◑	◔	◔	○	◔	○
MICHAEL ABRAMOVICI ET AL. (2011)	◕	●	◕	◕	○	◕	◕
MICHAEL ABRAMOVICI ET AL. (2009)	●	◕	◕	◑	○	◑	◕

Table 5: Literature review results.

[215] Cf. Beom Suk Jin et al. (2013), Development of a Continuous Usage Model for the Adoption and Continuous Usage of a Smartphone

[216] Cf. Patrick Klein et al. (2019), Towards an Approach Integrating Various Levels of Data Analytics to Exploit Product-Usage Information in Product Development

[217] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study

[218] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study

[219] Cf. Michael Abramovici et al. (2009), Knowledge-Based Feedback of Product Use Information into Product Development

[220] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development

Based on the literature evaluated, it can be concluded that the methodology to be developed as part of this study needs to meet the following requirements. First of all, the methodology should focus on machinery and engineering plants, and it should model the usage phase of them. Moreover, it should use real time data obtained from the usage phase in order to adapt the product functions to satisfy the user´s requirements. Therefore, the methodology to be developed should filter and consider the more relevant requirements, which are those that have more impact on the real usage of the product and link them to specific product functions. In conclusion the methodology should serve as a tool to improve the product functions of machinery and engineering plants basing this improvement on PUI.

4 Methodology Development

The main objective of this thesis is to develop a model that enables to use PUI in machinery and plant engineering for the validation of assumptions from product development in order to improve the next generation of products. The literature review discussed in Chapter 3 promises to improve the future generation of products basing the development of these next generations on PUI. The examined literature focuses on the extraction of the data from the usage phase and how it can be used, therefore it serves as a guideline for the approach presented in this thesis.

In this fourth chapter the methodology of this thesis is developed following the three target areas mentioned in Chapter 3. First of all, in Chapter 4.1, the modelling of the usage phase for a generic engineering plant and a machine will be developed. Then Chapter 4.2 will describe the filtration of the requirements to be considered and the linkage of these requirements to the product functions of a machine. In Chapter 4.3 the method for the consideration of the variation on the product usage, regarding on how the user can influence the product performance by adjusting the settings or characteristics of the product functions will be presented.

4.1 Modelling of the usage phase

In this section a theoretical model of the usage phase of both an engineering plant and a machine will be developed. It is of vital importance to have a cleared and structured model of the usage phase because the product functions can be more easily identified and subsequently analysed in order to improve or eliminate them. Moreover, this model serves for a general understanding of how the products and their functions are being used during the usage phase.

4.1.1 Modelling of an engineering plant

First of all, as mentioned above, the methodology includes the modelling of a theoretical engineering plant. It is important to have a model of the entire plant to be able to observe the complete process from the moment the raw materials enter the production line until the final product leaves the factory. This whole process usually has several different machines where the product goes through each of them in a sequential way. Each machine has a unique role within the plant, so the product functions of each machine are different, as well as the way in which the operator uses them.

For the representation of this model, it has been used the K3 method due to the fact that it's a graphic descriptive language for modelling work processes and it is process orientated. The K3 method is developed on the basis of the internationally standardised graphical modelling technique for activity diagrams according to the Unified Modelling Language (UML). K3 uses so-called swim lanes to model organisational units. Depending on the desired level of detail, a swim lane can represent a single person, a group of persons, a department, a division, or an entire company.

Within each swim lane, the activities which describe actions or operations in the process flow are represented.[221] According to the VDI Guideline 3633 an activity is defined as a time-consuming process, which is limited by an initial and leads to a and a final result through a state transition.[222] The figure bellow shows the K3 graphical description for a theoretical engineering plant.

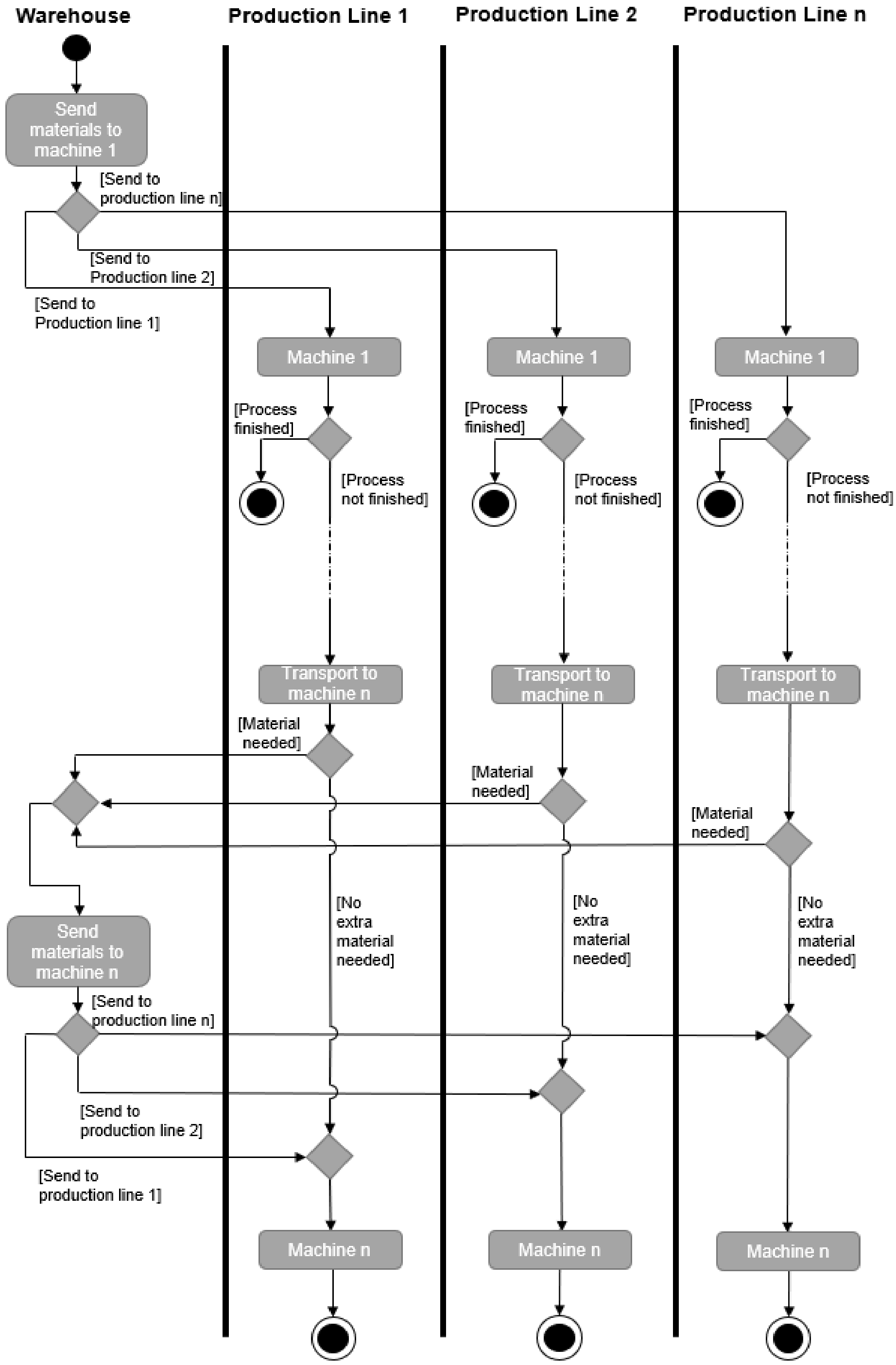

Figure 34: K3 diagram of an engineering plant usage phase.

221 Cf. Kausch, B. (2010) Integrative Methodik zur grafischen Modellierung und dynamischen Simulation von Entwicklungsprozessen am Beispiel der Verfahrentechnik.

222 Cf. VDI Guideline 3633 (2018), Simulation of systems in materials handling, logistics and production - Terms and definitions.

The model represented in *Figure 34* has been divided into different swim lanes and each of these swim lanes has different activities through which the products go through until they have completed the whole process. *Figure 34* illustrates the K3 model of an engineering plant with a warehouse where the materials are stored and three production lines. This model can be modified or adjust depending on each specific plant that needs to be modelled but serves as an example to simulate how the whole process must be structured. In each production line there are “n” different machines, and it has been assumed that the materials or components needed in each machine as well as the products that go out from the machines are transported manually. In the cases where the engineering plant differs from the one represented in *Figure 34* regarding to the number of production lines, machines within each production line or if it has an automated transport through the whole plant, the model can be adjusted to each case by eliminating or adding different elements.

The beginning of the production process is represented with the solid black circle in the warehouse and the finish of it with the double black and white circle at the end of each machine. It has been decided that at the end of each machine the process can be finished because in an engineering plant different products can be manufactured, and each product can have its own process hence it can go through different machines. The boxes in the model represent the tasks or activities that need to be done, such as sending the materials to each machine when needed or transport the products from one machine to another. These different boxes describe the progress in the process flow. The rhombus represents the decisions that need to be made throughout the process like for example to which production lines the materials need to be send or if the process is finished or the products need to be transported the next machine. The last elements that appear in *Figure 34* are the arrows and they illustrate the temporal-logical connection of the tasks and activities of the diagram.

4.1.2 Modelling of a machine

Once the engineering plant has been modelled and there is a clear overview of all the machines in the plant, the machines to be analysed during the usage phase so PUI can be obtained and subsequently used to improve the functions of the next generation of machines need to be modelled. In this section a flow diagram of a theoretical machine will be developed representing all of its different functions with different operating modes.

The purpose of modelling the machinery within the plant is to have a general representation of how the functions within the machine are assumed to be used and compare it to how they are actually used during the usage phase. Furthermore, the model of the machine will serve to identify more efficiently each function throughout the whole workflow of the machine to obtain information about them and later improve them or delete them if they are not being used by users. The modelling of a standard machine illustrated in *Figure 35* is represented with a flow diagram with the aim of describing step by step the complete usage phase of the machine in order to build a big picture of how the product functions are being used.

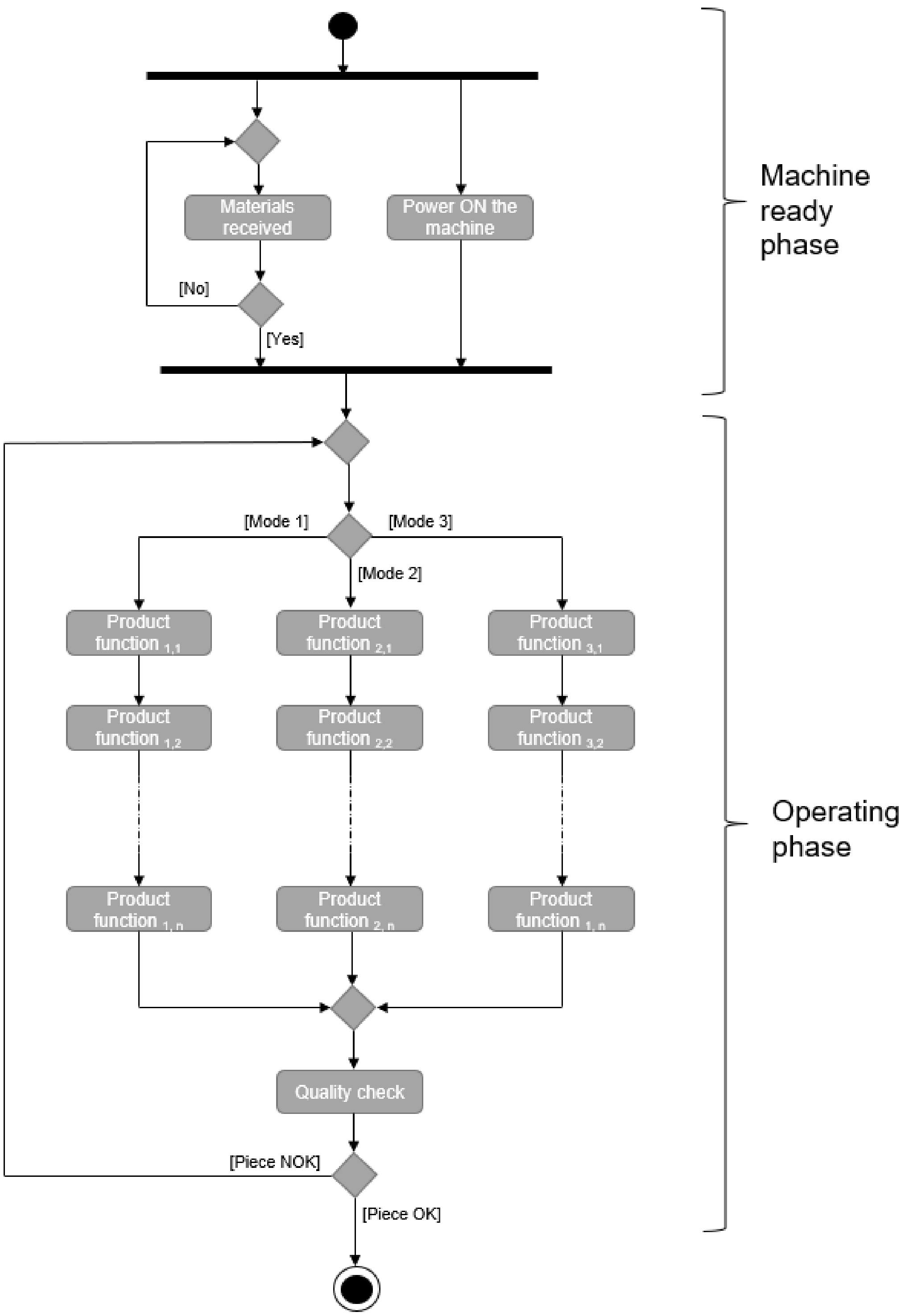

Figure 35: Flow diagram of a machine usage phase.

The modelled usage phase of a theroretical machine represented in the figure above is divided into two main parts, the machine ready phase and the operating phase. This is similar to the approach of HARJA where the usage phase was divided into three different phases: Power On phase, Machine Ready phase and Spindle Running phase. [223]

[223] Cf. H. Harja et al. (2018), Preliminary Development of Real Time Usage-Phase Monitoring System for CNC Machine Tools with a Case Study on CNC Machine VMC 250, p. 3

In the methodology developed in this thesis, the “Power On phase” has been included inside the machine ready phase. In addition, since this methodology focuses on a generic type of machine, the different functions that a machine can perform are included within the operating phase.

The first phase that appears in *Figure 35* is the Machine ready phase which consist in two main activities that are carried out in parallel. The first activity is the reception of materials, components or pieces from the warehouse or a previous machine. The second activity is the machine start-up or power on. Different machines can be switched-on in different ways, but in this case, it is assumed that the machine is switched-on by pressing a switch-on button. Once these activities are done the next phase, called the operating phase, can begin.

Inside the operating phase it is shown all the different product functions of the machine under different machine operating modes. The flow diagram of the usage phase in the figure above is represented with three different operating modes due to the fact that a machine can have different operating modes which offer different function performance. If a specific machine has more or less modes, the flow diagram can also be adjusted to model the usage phase for specific cases. Inside each operating mode the different product functions that the machine has can be found, which are carried out sequentially until all the functions needed to complete the process have been conducted. Once all the product functions have been carried out there is a quality control of the resulting products or pieces where it is checked whether the items produced meet the quality standards of the user. If the piece meets the quality standards it means that the process is finished, therefore the piece can move to the next machine in the production line. However, if the item does not satisfy the quality standards set, the item must be reworked and the whole process repeated. In the cases where the machine allows to repeat a specific product function individually when needed, the flow diagram must be adjusted to such case as shown in *Figure 36*.

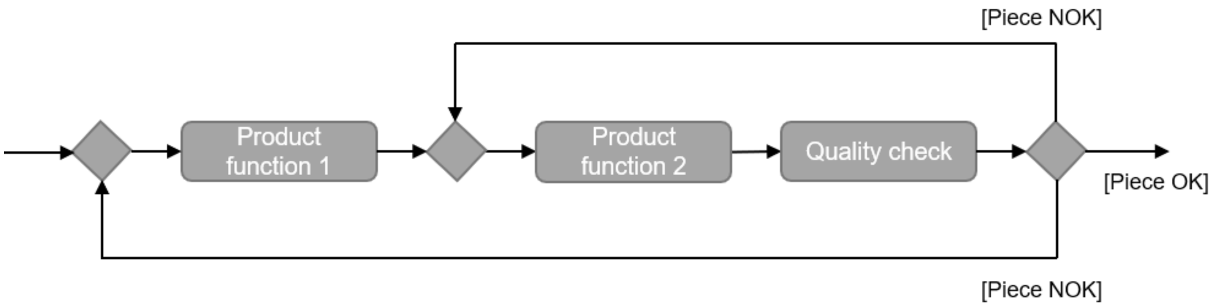

Figure 36: Repetition of individual functions.

As in the diagram in *Figure 34* from the previous section, the beginning and end of the process is represented with a black circle and a black and white circle respectively. The activities or tasks are represented with boxes and the rhombus describe the decisions that need to be made, such as on deciding on the operating mode. Whereas the arrows show the temporal-logical connection of the tasks and activities in the diagram.

4.2 Filtration of requirements

The objective of this second part of the methodology presented in this thesis is to identify the product functions of product *m*, that are being used in the usage phase in order to detect which aspects of the product are most relevant for the users. Furthermore, the requirements of the users will be linked to the mentioned product functions. This will facilitate the improvement of these functions in the design of the next product generation *(m+1)* as the real needs of the users will be better known and their requirements will be more easily fulfilled.

As in the design of the first generation of the product *m* there is no information about the usage phase of the product, hence the requirements are obtained from the information of the product manager, the marketing and sales department. Therefore, the product functions will be based on the usage hypothesis so that they satisfy the assumed requirements of the users. Once information from the usage phase of the product *m* is available, the user requirements can be evaluated and compared to the requirements of the usage hypothesis. If the requirements are not being met, the product functions of the product *m+1* must be redesign according to the requirements information from PUI. Therefore, it must be analysed whether the requirements are being fulfilled by the functions or whether the functions need to be improved to better satisfy the user requirements. In addition, if new requirements appear, new functions need to be created in order to fulfill these new requirements. *Figure 37* shows the sequence of how the user's requirements on the product are implemented to enhance the product functions of the next generation.

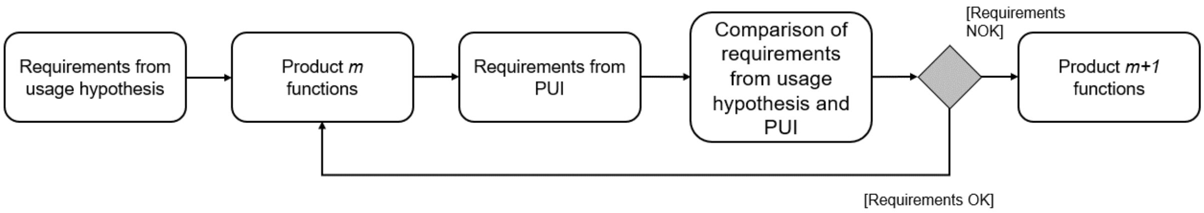

Figure 37: Development of product functions from customer requirements.

When the requirements have been analysed, the requirements should be related to the product functions to see which requirements are fulfilled by which functions. As already mentioned, the requirements must be unique, complete, achievable, measurable, and not contradictory among other characteristics described in Chapter 2.4. [224] *Figure 38* shows how the requirements must be linked to the product functions and illustrates all the possible cases considered, where one requirement can be satisfied by one or more product functions and one product function can fulfill one or more requirements.[225]

[224] Cf. Project Management Institute (2016), Requirements management.

[225] Cf. Daniel P. Politze et al. (2009), Exploitation Method for Functional Product requirements – An Integrated Function Oriented Approach, p. 1.

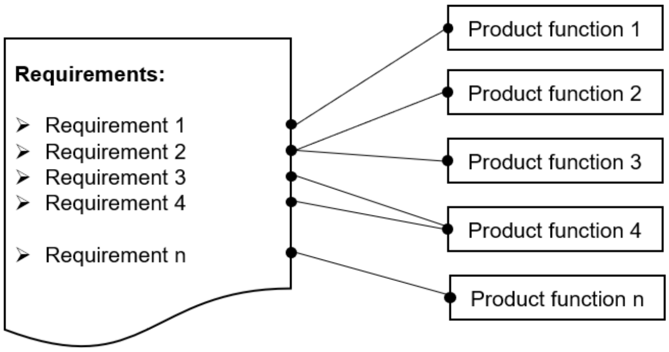

Figure 38: Derivation of relevant product functions from requirements.

4.3 Variation of product usage

One of the key aspects of the methodology developed in this presented work, is to focus on the product functions which can be manipulated by the operator during the usage phase, affecting the performance of them and the product itself. Analysing these product functions that can be adjusted and manipulated by the user results in a better understanding of how the users uses them, if they are being used properly, or if they are not being used at all. Although the overall function of the machine is the same, each user can manipulate the machine in different ways or even use different functions of the machine. Therefore, when analysing the use of these product functions, different usage scenarios can be observed that may not have been considered by the developers when designing the machine.

The methodology developed considers the variability of these product functions during the usage phase and they have been divided into four distinct groups according to their types of variability: temporal, qualitative, optional variability, and repetitive variability. *Table 6* shows the classification of the types of product variability as well as some example questions which will help the user of the methodology classify the functions according to their variability.

Types of variability	Description	Example questions
Temporal variability	The function can be activated or terminated by the user	Can the user start or end the function by his own means?
Qualitative variability	The function can be qualitatively adjusted by the user	Can the user adjust the settings of the function affecting its performance?
Optional variability	The function can be activated/terminated by several alternative actions	Can the user choose an alternative function to do the operation?
Repetitive variability	The function was not performed correctly, so the user repeats the process or the function	Is the function or process being repeated due to a malfunction?

Table 6: Types of product function variability.

As shown is *Table 6* the temporal variability refers to those functions which can be started or stopped by the user at any moment. The user can activate the function depending on several factors like for example if the raw materials are not ready and user needs to postpone the start of the function, or the item or machine needs to cool down due to overheating caused by previous functions. Furthermore, it is also considered that a user can stop the function before it is terminated for several causes such as failures or safety reasons. By extracting PUI on the temporal variability of product functions, it is possible to observe which functions are postponed or interrupted during the machine usage phase. This usage information serves to analyse why and when the product functions are being started or stopped by the user. Therefore, the product functions can be adjusted to improve the performance and efficiency for the future machine generations.

The second type of variability considered is the qualitative variability and refers to those product functions which can be adjusted qualitatively by the user depending on the type of operation the machine is going to do or the product to be made. Qualitative variability encompasses all aspects of a function that can be introduced by the user, such as speed, temperature, pressure, or tolerances that directly affect the product to be machined. By extracting usage data from these types of functions it can be obtained the range of the performance values introduced by the operators during the machine. The maximum and minimum working values of the machines can also be analysed. With all this it is possible to calculate the average operating values as seen in the approach form LÜTZENBERGER and adjust the product functions more precisely to the actual use of the machine.[226] This will help to reduce over-engineering in the development of the next generation of machines, which wastes a lot of resources and increases the price of the product unnecessarily.[227]

The optional variability functions includes all functions which may or may not be used by the user, i.e., during the working phase of the machine they do not have to be activated as there are alternative functions that can accomplish the same operation. By examining the usage phase of the machine, it can be determined which of these functions are being used or not used by the users. Therefore, these functions can be eliminated in the next generation simplifying the product itself and the resources can be focused on the development of other functions that are being used and satisfy the real requirements of the consumers. In addition, the cost of manufacturing the product can be reduced, increasing profits, or even allowing the price of the product to be reduced in order to make it more competitive in the market and attractive to consumers.

The fourth type of product function variability that can occur during the usage phase is the so-called repetitive variability and refers to the product functions which were not correctly done by the machine and the user decides to repeat them. When the machine has completed all its functions, the operator can carry out a quality control on the item produced.

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[226] Cf. Johannes Lützenberger et al. (2016), Improving Product-Service Systems by Exploiting Information from The Usage Phase. A Case Study, pp. 378-381

[227] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

The quality control can be carried out either manually or by means of sensors that can detect that there is a defect on the item and hence a failure in the process. Once the failure has been detected and identified, the user decides whether to repeat the whole process as shown in *Figure 35* or, if possible, only repeat the function that has produced the failure. By detecting the functions that have to be repeated because their performance is not satisfactory, it is possible to identify the weak points of the machine, as explained by ABRAMOVICI in his approach, in order to correct them and improve these functions in the future generations. [228] When these functions are improved in new machines generations and no longer have a negative effect on machine performance, they should be considered as temporal, qualitative, or optional variability functions depending on their characteristics.

4.4 Interim conclusion

In summary, in this Chapter 4 a methodology has been developed which facilitates the improvement of the product functions of a future machine based on information obtained from the usage phase of the machine from a previous generation. This methodology could be described as a three-step model where first the usage phase of an engineering plant and the machine to be improved is modelled. Then a filtering of the most relevant requirements is conducted, and these requirements are associated to the product functions. Finally, these functions are classified according to the type of variability they may show during their usage, in order to subsequently analyse their performance and improve them to satisfy the user's requirements.

In the modelling of the usage phase, the first step is the modelling of the engineering plant, which serves to obtain a general overview of the manufacturing process and to be able to observe which machines are part of it. Once the plant is modelled, a model of the machine or machines to be analysed is made. This model describes the different functions of the machine as well as the order in which the machine performs them. This gives an overview of the functions of the machine to make it easier to identify, classify and analyse them.

In the second step of the methodology, the most important requirements are filtered, which are those that have a major impact on the improvement of the product and directly affect the product's functions. In addition, these requirements are obtained from the usage phase of the product and are linked to the product functions which fulfill them.

In the last step, the product functions are classified depending on the type of variability of these functions. The types of variability have been divided into four groups: temporal, qualitative, optional and repetitive. This enables a detail analysis of the usage phase of the machine to better understand how users use the product functions in order to be able to adapt them according to their requirements in the next generation of machines.

[228] Cf. Michael Abramovici et al. (2011), Decision support for Improving the Design of Hydraulic Systems by Leading Feedback into Product Development, p. 6

5 Evaluation of the Methodology

After discussing the theoretical design of the methodology in Chapter 4, in this fifth chapter, the methodology is evaluated. It has been decided to implement the methodology on a 3D printer, model RoboxPRO of the manufacturer CEL. In the case study analysed, the RoboxPRO printer is used for the fabrication of tools for the production line of a hardware manufacturing company. In the following, first the usage phase model of the hardware manufacturer engineer plant and the 3D printer will be developed, then the customer requirements will be filtered and linked to their relevant product functions and finally the product functions of the machine will be classified according to their type of variability. At the end of this chapter the key insights from the evaluation will be discussed.

5.1 Modelling of the 3D printer usage phase

First of developing the model for the usage phase of the presented case study, the usage phase of the engineering plant of a hardware manufacturer is going to be modelled. This gives an overview of all the machines in the plant and the whole production process. Moreover, the methodology could be applied to all of the different machines, but this evaluation is going to focus on the usage phase of the RoboxPRO 3D printing system. Within the plant, the 3D printer is in charge of producing different tools to protect certain components of the product when the product is going through the coating machine.

Figure 39 illustrates how the engineering plant is divided into four main areas: the warehouse, the 3D printing area, production line 1 and production line 2. The warehouse stores all the materials and components needed to manufacture the electronic cards. From here, materials and components are sent to the production lines and the 3D printing area. In the case of the 3D printing area, different materials such as ABS or nylon are sent depending on the tool to be produced.

It can also be seen in *Figure 39* that there are two different production lines in the engineering plant. However, it should be noted that both consist of the same machines and the same products can be manufactured on them. One production line or the other is used depending on the workflow and workload. Within each production line, the process starts in the welding area where the motherboard and components such as diodes and capacitors needed to build the electronic card are received from the warehouse. In the welding machine the components are welded to the motherboard. The cards are then transported to the coating machine, where the most critical components of the electronic cards are first protected with 3D printed tools. Once the printed tools have been inserted, the machine adds a layer of coating to the product. Afterwards, the cards are transported to the packaging area where they are packed and ready to be shipped.

As already mentioned, in the 3D printing area, materials are received from the warehouse and tools are printed to provide protection for the most critical components when applying the coating layer in the coating machine. This whole process is described in more detail in *Figure 40* where the model of the usage phase of the RoboxPRO 3D printer is shown.

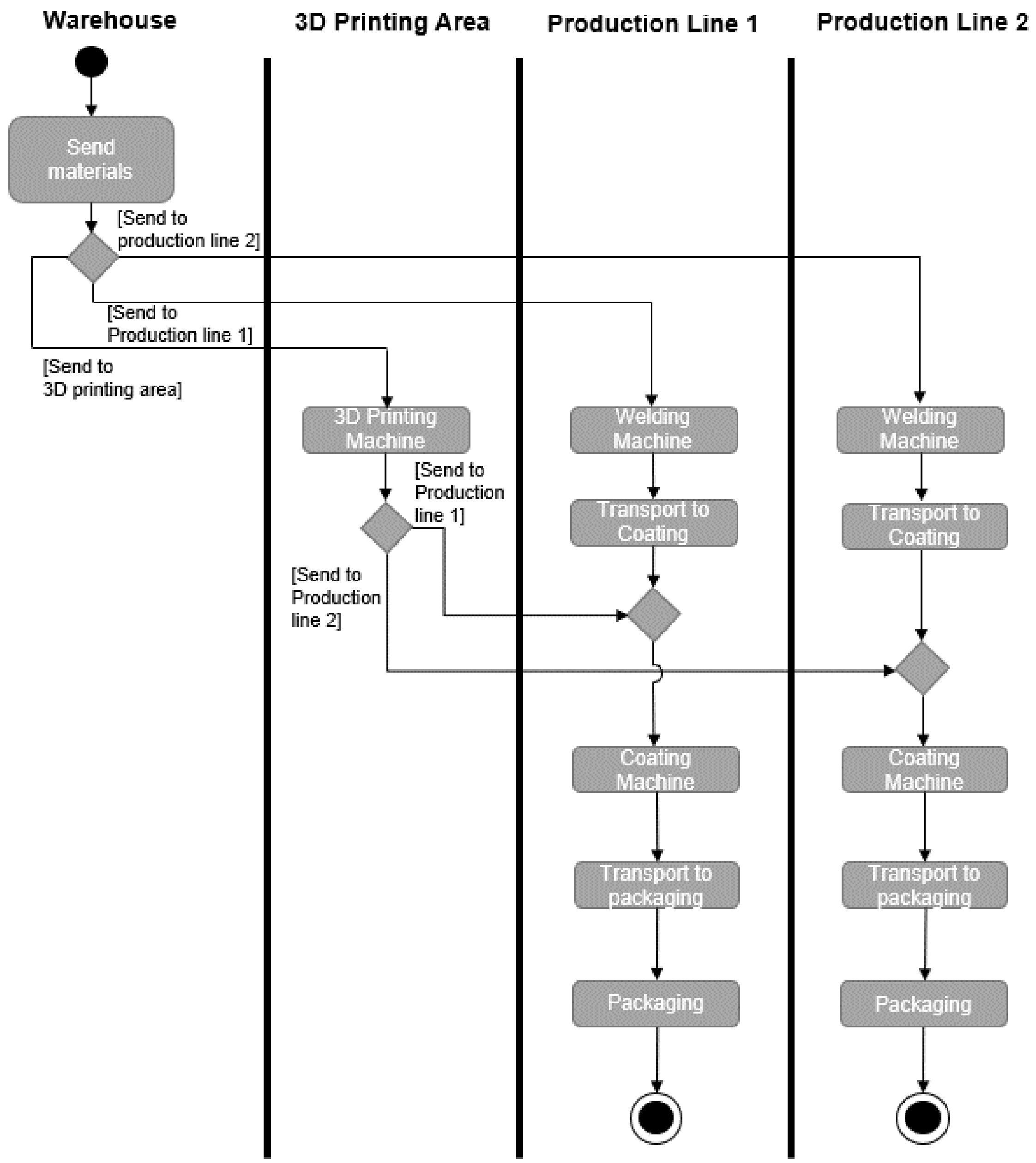

Figure 39: Hardware manufacturer engineering plant.

After the entire process within the plant with its various machines has been analysed, the 3D printer usage phase is modelled. This model is intended to describe the whole process carried out by the machine to produce the pieces and to better identify the different functions conducted by the printer. This will give an insight into where in the printing process the product functions are not performing as expected. Once these functions have been identified, they can be improved or adapted for the next generation of printers. In *Figure 40* the usage phase model of the RoboxPRO 3D printer is shown.

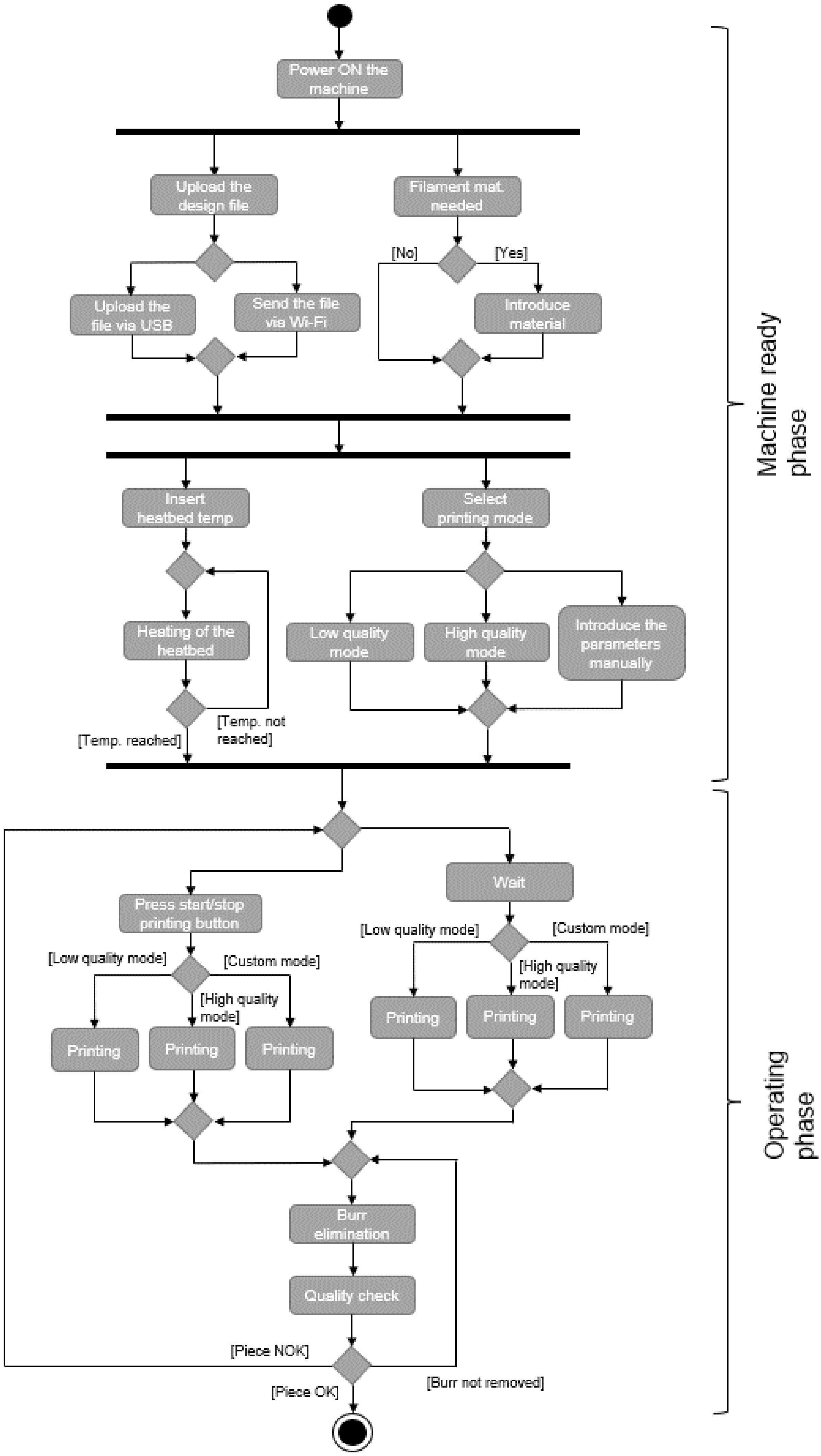

Figure 40: RoboxPRO 3D printer usage phase.

As explained in Chapter 4, the model has been divided into two phases, the machine ready phase and the operating phase. The machine-ready phase starts with the switching on of the 3D printer. This is followed independently, by the loading of the design file, which can be done via USB or by sending the file over the internet, and on the other hand by the insertion of the printing material, if necessary. Then the user must enter the desired heatbed temperature and select the printing mode. The heatbed is responsible for heating the base of the 3D printer, so that the printed pieces remain adhered during the printing process. This prevents or reduces wrapping (parts peeling off and bending during the printing process). The user also has to select one of the three available print modes. In the high-quality mode, the printing operation time takes longer because the printing speed of the machine is lower, but the quality of the piece produced is very high. On contrary, the low-quality mode has short printing times due to high printing speeds resulting in inferior quality pieces. The third operation mode is the custom mode, where the user introduces the parameters of printing temperature, printing speed, layer height, shell thickness, bottom/top thickness, and fill density depending on the characteristics of the piece he wants to fabricate. Once these functions are performed the machine ready phase is completed and the operating phase can start.

In the operating phase the user must first decide to press the “start/stop” printing button to begin the printing operation or wait 5 seconds for the printer to automatically start printing the object in the selected printing mode. When the piece has already been printed, the machine carries out the burr removal function to eliminate the burr that has been produced during the printing process. A quality control is then applied and if the piece is well printed, the process is finished. If the piece has not been printed correctly, it must be reprinted. If the burr has not been completely removed, this function can be repeated individually.

5.2 Filtration of the 3D printer requirements

The second step of the developed methodology is the filtering of the most relevant requirements for consumers and match these requirements to the functions of the 3D printer. The information about the requirements of the consumers should be obtained according to the methodology from the usage phase of the 3D printer. With this PUI it can be analysed in a more realistic way which functions fulfil which requirements of the users, which new requirements appear, or which requirements are not important because the functions are not frequently used in the usage phase. Unfortunately, it was not possible to obtain information during the printer´s usage phase, so the most important requirements considered were obtained from forums, blogs, social media, and websites. These considered requirements are functional requirements that directly affect the performance and quality of the printer as well as other functions that facilitate the management of the 3D printer. The table below shows the requirements and links them to their appropriate product functions.

Req. id.	Requirements	Product functions
1.	High printing speed	Low quality mode (printing speed: 500 mm/s)
		Nozzle temperature up to 350ºC
2.	High printing quality	High quality mode (layer resolution: 0,05mm)
3.	Easy to handle and select programmes	5” touchscreen interface
4.	Connectivity	File transfer via USB (USB cable or USB stick)
		File transfer via internet (Wi-Fi)
5.	Wide range of printing materials	Printing materials: ABS, PETG, PC, nylon & carbon-filled
7.	The printer maintains a constant temperature	Enclosed 3D printer
		Nozzle (Nozzle temperature maintains constant)
		Heatbed (Heatbed temperature maintains constant)
8.	Good Heatbed	Heatbed temperature up to 150ºC
9.	Ability to print large pieces	Printing dimensions (LxWxH) 210x300x400mm
		Heatbed temperature up to 150ºC
10.	Good surface finish of the piece	Burr elimination function
11.	Ability to stop printing operation	Start/stop button

Table 7: Customer requirements linked to RoboxPRO product functions.

As illustrated in *Figure 38* from Chapter 4, one requirement can be fulfilled by one product function like requirement 3 or requirement 10 which are satisfied by the 5” touchscreen interface and the burr elimination function respectively. Requirements 1, 4, 7 and 9 are achieved by means of several product functions. For example, if we focus on requirement 9, users demand that the printer is able to print large pieces and this is achieved with a large printing surface volumes and with high heatbed temperatures, which allows the pieces to adhere to the base during the printing process. Furthermore, there are product functions such as the nozzle that satisfies requirements 1 and 7 or the heatbed that helps to fulfil requirements 7, 8 and 9.

5.3 Variation in the 3D printer´s usage

In the previous section, the user requirements were identified and linked to the product functions that meet these requirements. Therefore, the third step of the methodology is applied in this section. In the following, those functions that show a certain degree of variability during the usage phase of the 3D printer will be classified according to the type of variability as explained in Chapter 4.3. *Table 8* shows the four types of variability considered in this thesis (temporal, qualitative, optional, and repetitive) and which product functions are classified under each variability type with a brief explanation.

Type of variability	Product functions	Explanation
Temporal variability	Start/Stop button	The user can start/stop the printing operation by his own means
Qualitative variability	Heatbed temperature	The user introduces the desired bed temperature
	Custom printing mode	The user introduces the desired parameters
Optional variability	USB port	The user can choose between two functions (USB or Wi-Fi)
	Wi-Fi connection	The user can choose between two functions (USB or Wi-Fi)
	High-quality printing mode	The user can use another mode
	Low quality printing mode	The user can use another mode
Repetitive variability	Burr elimination	The user can repeat this function when it does not perform correctly

Table 8: Types of variability of the RoboxPRO 3D printer.

The “Start/Stop” function has been classified under temporal variability due to the fact that it allows the user to directly influence the duration of the process by stopping or starting it when necessary. The user can stop the process by pressing the button when for example the printer is running out of material before finishing the piece and more material needs to be fed into the machine. Once the material has been fed into the machine, the user can press the button again to continue the printing process, thus increasing the printing time.

Under qualitative variability the product functions of the heatbed and custom printing mode have been classified. Within these product functions the user introduces the desired parameters which depend on the type, size, quality, and material of the object to be printed. Therefore, with the parameters entered the user directly influences the performance of the machine. In addition, in the usage phase it can be observed which are the maximum, minimum and average parameters introduced in these functions to subsequently adjust them in the next generation of 3D printers in order to reduce the overengineering of the product and adapt it to the user´s real needs.

The optional variability functions considered in the RoboxPRO 3D printer are those functions which can be carried out by several alternative functions. The USB port and the Wi-Fi connection have been considered under this type of variability because the user can choose one connectivity function or the other. Furthermore, the high-quality and low-quality printing modes show an optional variability because the same piece can be printed in both modes although the operation time and quality of the printed object will be different. During the usage phase of the printing machine, it can be analysed which of the optional variability functions are being used or not, to comprehend why and improve them in the following product generations.

The last variability type is the repetitive variability and the function of the burr elimination, used to improve the surface finish, has be linked to it. The burr elimination function has been considered a repetitive variability function because the user can decide to perform this action again if the outcome of it is not the desired one. If during the usage phase it is observed that users repeat many times this action it clearly reflects that it doesn´t fulfil their requirements and hence it must be improved.

5.4 Interim conclusion

In this Chapter 5 the methodology developed in Chapter 4 has been applied to the RoboxPRO 3D printer used for the fabrication of tools for the production lines of an engineering plant of a hardware manufacturer.

First of all, in Chapter 5.1, the usage phase of the engineering plant was modelled using the K3 graphical descriptive language. The plant was divided into 4 different swim lanes: the warehouse, 3D printing area, production line 1 and production line 2. Inside each swim lane the production process of the engineering plant with the machines involved was represented, as it is shown in *Figure 39*. Within the plant, the usage phase of the RoboxPRO 3D printer was modelled, like it is illustrated in *Figure 40*. All the functions of the machine where modelled and also their relations between them and the decisions users are able to take during the usage phase of the printer. The outcome of this model shows a global and structured view of the different functions of the printer so that they can be more accurately identified and later analysed and classified in the following steps of the methodology.

In Chapter 5.2, the second step of the methodology was applied. Here the most important requirements were identified and linked to their relevant product functions. Unfortunately, there was no access to real PUI from the 3D printer to analyse the real usage of the machine and derive the user´s requirements from it. The requirements considered in this chapter were obtained by analysing the information from different websites, forums, and social media. After the product requirements were identified there were linked to the product functions of the RoboxPRO printer which satisfied these requirements.

The last step of the methodology, which focuses on the analysis of the variation of product use during the usage phase, was conducted in Chapter 5.3. In this third step, the product functions were classified according to their types of variability shown during the usage of the printer. The variability considered in the methodology are, temporal, qualitative, optional, and repetitive variability. Moreover, it can be stated that the developed methodology focuses on how the usage of product functions can affect product performance. By classifying functions according to their variability during the usage phase, the strengths and weaknesses of the functions can be analysed more precisely in order to improve or adapt them in future product generations.

In conclusion, after having applied the methodology developed in this thesis to the RoboxPRO 3D printer, it has been possible to describe in detail the usage phase of the machine. This description of the usage phase of the machine can be further processed as a basis for the analysis of the actual usage of the printer by the users in order to improve its functions. By improving the functions in the next generation of RoboxPRO 3D printers, the requirements of the users will be met more effectively and consequently the product will be more successful in the market.

6 Conclusion

This chapter presents the conclusion of the thesis where the most important aspects of the research will be analysed in detail. In Chapter 6.1, a summary of the developed thesis is provided illustrating the whole research process. In the following chapter, Chapter 6.2, a conclusion of the methodology will be presented and the evaluation of it will be discussed. Finally, in Chapter 6.3, an outlook on the potential future researchs in the context of this thesis will be given.

6.1 Summary

In this thesis a methodology was developed to describe and model machinery and engineering plants with the information obtained from their usage phases. The output of the methodology can be used for the validation of the assumptions from product development and subsequently improve future generations. To accomplish this main research objective, a three-step model is developed, were first the usage phases of engineering plants and machinery is modelled. Then a filtering of user´s requirements is performed, and these requirements are linked to the relevant product functions. Finally, these product functions are classified according to their type of variability. In order to develop the methodology, it has been necessary to carry out a detailed study and analysis of current studies on this field throughout the thesis.

In the first chapter, the background and research questions are presented. This is followed by the objectives of the thesis, which establish the framework of the methodology to be developed. Afterwards, a thesis structure is outlined, which serves as a basis for the elaboration of the following chapters.

Chapter 2 discusses the fundamentals and definitions that provide the contextual basis for developing the required model. First, the definition of the Product Life Cycle with its seven differentiated phases is given. As the methodology to be developed centres on the product usage phase, the definitions of product usage and product usage information (PUI) are presented. Next, the terms product functions and product model are highlighted to clarify the different parts and functions that make up a product. Additionally, definitions of customer value and customer requirements are provided to better reflect the actual needs of the user. The last concept introduced in this second chapter, is the concept of Industry 4.0. Inside the Industry 4.0 this thesis focused on the terms of cyber-physical systems (CPS) and the Internet of Things (IoT), both of which describe the vision of future smart products which will be capable of obtaining information during usage and communicating with other systems.

In Chapter 3 a structured literature review of the existing approaches in the context of this thesis is conducted. Therefore, in this chapter the evaluation criteria are defined with the target and object area of the thesis. The evaluation criteria constitute the basis for the methodology developed in the subsequent chapter. Furthermore, at the end of the chapter an overview table which analyses the evaluation criteria of the reviewed papers is provided. With this table the research gap between the different approaches considered and the methodology developed was outlined.

In the fourth chapter, the methodology of the thesis is developed. As stated above it consists of three clear steps that cover the target areas which are presented in Chapter 3. The first step of the methodology describes the modelling of the usage phase of machinery and engineering plants. In the second step the more important user requirements are identified and matched to the product functions which are able to fulfil them. Finally in the third step the product functions are classified according to their variability type. The variability types considered in the methodology are temporal, qualitative, optional, and repetitive.

In Chapter 5, an evaluation of the methodology developed in the thesis is performed. The methodology was applied to the RoboxPRO 3D printer which is used to print tools for the production line in a hardware manufacturing plant. First, the usage phase of the engineering plant and the RoboxPRO was modelled. Afterwards, the requirements were identified and filtered to subsequently link them to the printer´s product functions. The third step of the methodology was also conducted; therefore, the product functions were classified according to their type of variability.

6.2 Methodology conclusion

It can be concluded that with the methodology developed in this thesis, the central question of the research, “how can the product usage in machinery and plant engineering be described and modelled as a basis for the validation of assumptions from product development?”, is answered. By applying the methodology to engineering plant machinery, the usage phase of the machines can be modelled, and subsequently the information from the usage phase can be processed to filter out the most important requirements for the users and match them with the appropriate product functions. In the last step of the methodology the product functions can be classified according to the variability shown during the usage phase of the machine. Therefore, the outcome of the methodology can be used to validate the assumptions from the usage hypothesis made in the product development phase in order to design products that better meet the needs and requirements of the users in the next product generations.

This thesis contributes to exploit the enormous potential of the knowledge generated during the usage phase of a product.[229] As seen in Chapter 1, there is a trend on transforming machines and systems in engineering plants into cyber physical products and systems (CPS).[230] This is becoming possible due to the small size sensors that can be embedded in products, their decreasing price and advances in information technology that increase access to usage information of current products, which can be used in future generations of products.[231] Hence, by applying the methodology, it will be possible to take advantage of the PUI obtained from the CPS in order to use it for further development of future generations of products.

[229] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, pp. 116-117

[230] Cf. Schuh et al. (2020), Always Beta - DevOps für cyber-physische Produkte, p. 116.

[231] Cf. Abramovici and Lindner (2011), Providing product use knowledge for the design of improved product generations, p. 211.

The developed methodology supports the developing teams on modelling, structuring, and classifying product functions according to the user´s requirements based on PUI obtained from the usage phase. The output information from the methodology can be used as a tool for developers to improve the subsequent product generations as the user´s requirements will be better captured, and more precisely fulfilled.

6.3 Outlook

The theoretical framework of the methodology, as well as its application, validated through the RoboxPRO case study in Chapter 5, successfully provide an adequate solution to the resulting research gap. In this chapter, the aspects where the methodology could be further developed, and future research potential areas are discussed.

Firstly, it should be emphasized that the methodology developed does not specify how information from the product usage phase can be obtained. It has simply been assumed that such information is accessible and available so that the methodology can then be applied. Furthermore, the methodology has only been applied to one case study as it can be seen in Chapter 5, hence it could be applied to more case studies to be able to further refine and validate it. In addition, when the second step of the methodology was applied to the RoboxPRO 3D printer, it was not possible to obtain PUI, so it would be interesting to be able to repeat this step with real information from the usage phase of the printer.

In terms of potential future areas of study for this thesis, a procedure for obtaining the PUI used in the methodology could be developed. It should also be analysed how to use the results obtained after applying the methodology for the validation of the assumptions made in the product development phase. This would make possible to see if the functions developed in product *m* using these assumptions meet the requirements of the users and if not, to improve them in the next product generation, *m+1*. Finally, this procedure could be extended so that it is also possible to detect and identify innovation potentials based on the information obtained during the usage phase of a product.

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