MASTER

On the road towards smart manufacturing
a framework to support the development of smart manufacturing

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On the road towards Smart Manufacturing

A Framework to support the development of Smart Manufacturing

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Abstract

The fourth industrial revolution is leaving its mark on society, influencing technology, business, and lifestyle. Similarly, to the three previous revolutions, it is expected to drastically change the manufacturing domain. The change in the manufacturing domain is also known as the smart manufacturing initiative. Companies that want to join and stay competitive need to adapt their operations by incorporating Information Technology and include the characteristics of smart manufacturing. These characteristics include horizontal, vertical and end-to-end integration supported by Information Technology. In this research, a framework is established that supports enterprises in pursuing smart manufacturing capabilities, based on their changing IT architectures. To extract the relevant elements of smart manufacturing, existing reference architectures are analyzed. Based on the outcome the elements that need to be included in the framework are known. These elements are structured in a framework according to various stages, that visualizes a roadmap for smart manufacturing functionalities. The resulting framework is implemented and the performance is evaluated.
Preface

This thesis is the result of a six-month graduation project for the Master Operations Management and Logistics at Eindhoven University of Technology (TU/e), performed at Atos. This report also marks the end of my six years as a student. I would like to take this opportunity to thank the people who supported me along this journey.

First, I would like to thank my mentor Paul Grefen. Paul, thank you for your support in the past two years. Even though you were on a well-deserved sabbatical leave you still made time to discuss my project and I especially enjoyed our digital meetings, when one of us was across the ocean. You gave me unique opportunities that were extremely valuable for my personal growth and truly enriched my Master program. Second, I want to thank Irene Vanderfeesten as my second supervisor of this project. The input you delivered at the beginning of my thesis to direct me in the right direction and your constructive feedback throughout the process was of great value. I also would like to thank Jonno Erasmus, you might not be officially my supervisor, but through our discussions on the actual design of the framework, I was able to gain a lot from your experience in the manufacturing domain.

Next, I want to thank Atos and especially my supervisors, Hans Kwaspen en Ronald van Mersbergen, for giving me the opportunity and tools to conduct this research. From the beginning, you gave me a lot of freedom to choose a topic that suited me personally. This was challenging at first to get a clear understanding of the business needs but really benefited me at the end. I want to thank the Industry 4.0 team for their input and especially my fellow interns that created a great working atmosphere.

As said, this project also is the final chapter of my student life. Friendships are one of the most important things in life and I will cherish them forever. Girls, thank you for the great times, motivation and support you made the past years Formidable. I also want to thank the people from Interactie, Industria, and ESTIEM for the opportunities they gave me to develop myself. Special thanks go to my co-boardies from the 20th board of Interactie. Together we definitely reached new heights.

Without my parents, this result would literally not have been possible. They opened my eyes for the opportunities the technical university offered, which eventually led to me studying Industrial Engineering. Thank you for your unconditional support and always being there for me. The last person I want to thank is Olaf, my rock for the past five years already. Your listening ear, your joy and your down to earth view on things definitely helped me to complete this thesis.

_Nadja Brouns_
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<td>AFIS</td>
<td>Advanced Flexible Information System</td>
</tr>
<tr>
<td>BPMS</td>
<td>Business Process Management System</td>
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<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
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<tr>
<td>CDB</td>
<td>Customer Database</td>
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<tr>
<td>CPS</td>
<td>Cyber-Physical Systems</td>
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<tr>
<td>CRM</td>
<td>Customer Relation Management</td>
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<td>DSR</td>
<td>Design Science Research</td>
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<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<tr>
<td>ESB</td>
<td>Enterprise Service Bus</td>
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<td>I4.0</td>
<td>Industry 4.0</td>
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<tr>
<td>IIoT</td>
<td>Internet of Things</td>
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<td>IIRA</td>
<td>Industrial Internet Reference Architecture</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>IoT-ARF</td>
<td>Internet of Things Architectural Reference Framework</td>
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<td>IT</td>
<td>Information Technology</td>
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<tr>
<td>MES</td>
<td>Manufacturing Execution System</td>
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<td>MMS</td>
<td>Maintenance Management System</td>
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<tr>
<td>MOMS</td>
<td>Manufacturing Operations Management System</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>OT</td>
<td>Operational Technology</td>
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<tr>
<td>PDM</td>
<td>Product Data Management</td>
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<td>PLC</td>
<td>Programmable Logic Controller</td>
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<td>PLM</td>
<td>Product Lifecycle Management</td>
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<td>QMS</td>
<td>Quality Management System</td>
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<td>RAMI 4.0</td>
<td>Reference Architecture Model Industry 4.0</td>
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<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
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<td>SCM</td>
<td>Supply Chain Management</td>
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<td>SIBUS</td>
<td>Smart Factory Information Service Bus</td>
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<td>SWD</td>
<td>Software Development System</td>
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<td>WHMS</td>
<td>Warehouse Management System</td>
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Chapter 1

Introduction

The world around us is changing rapidly. One of the domains in which transformation takes place is the manufacturing domain. This transformation, also known as the fourth industrial revolution, is currently an important research area for both business and academia. This research project aims at developing a framework to support the implementation of smart manufacturing characteristics, by structuring technologies, systems, and activities. This project is carried out at Atos, a European IT services corporation.

Chapter 1 introduces the project showing its context, the problem definition and defining the research goal consecutively.

1.1 Problem Introduction

An industrial revolution is expected to drastically change the manufacturing domain. This fourth industrial revolution includes concepts as the Internet of Things (IoT), as well as servitization and Cyber-Physical Systems (CPS). It succeeds the three industrial revolutions that influenced the manufacturing domain many years ago, shown in Figure 1.1. To support this revolution, countries around the world contribute to research that enables this technology transformation (Thoben et al., 2017). The term 'the fourth industrial revolution' suggests that the impact of the revolution is only established in the industrial production and manufacturing domain. However, the impact manifests in various aspects of society, including technology, business, and lifestyle (Guoping, Yun & Aizhi, 2017). Nevertheless, most research has focused on the impact in global manufacturing and the fourth industrial revolution is even often referred to as Industry 4.0 (I4.0) (Pereira & Romero, 2017).

Industry 4.0 is not the only term related to this revolution in the manufacturing domain. Due to the increased amount of research in this domain, the concept of the fourth industrial revolution is somewhat fuzzy. Terms like smart manufacturing, Industrial Internet of Things and smart factory are country or even industry dependent. Therefore, there is a lack of a commonly accepted definition and a lack of understanding of the core concepts. Researchers do not even agree with each other if the initiatives are just different names for the exact same thing or they represent a different paradigm. Extending these terms beyond the manufacturing domain leads to even more initiatives with similar goals, such as smart home, smart grid and smart city. The diversity of initiatives, lack of a common understanding and lack of structure creates a challenge, which causes this revolution to still be at an early stage (Kang et al., 2016).

This project focuses on the effect of the fourth industrial revolution in the manufacturing domain, specifically smart manufacturing. Globalization increased the complexity of logistics flows as well as the growth of international competition, which leads to customers demanding personalized products and a shortened lifecycle of products (Douaoui, Fri, Mabroukki & Semma, 2018). The emergence of the
fourth industrial revolution in the manufacturing domain occurs due to the complexity and challenges at hand. Smart manufacturing, which is the increased application of collaborative manufacturing systems, throughout manufacturing and supply chain, is one of the focus areas in this worldwide research to cope with the current challenges (Davis, Edgar, Porter, Bernaden & Sarli, 2012; Kang et al., 2016). Corporations can use smart manufacturing to gain a competitive advantage, such as differentiation or cost reduction (Lu, Frechette & Morris, 2016). This means that for companies as well as academia there is a large interest to further develop and implement smart manufacturing (Davis et al., 2012).

According to Thoben et al. (2017), there are still numerous amount of issues in the field of smart manufacturing. One of the issues they point out is the lack of reference architectures, that serve as an abstract blueprint to structure a class of systems (Grefen, 2016b), especially for smart manufacturing. The complexity of the smart manufacturing ecosystem is illustrated in Figure 1.2. It shows three life-cycles, product, business, and production, including various lifecycle steps, as well as the manufacturing pyramid showing the hierarchical production layers. Furthermore, the ecosystem includes systems that support the lifecycle steps and information flows that connect the steps. A reference architecture can support in creating the clarity that is needed to connect the various technologies and elements within the smart manufacturing paradigm. Currently, there is no framework available that includes standards or provides structure for new technologies, such as the Internet of Things, cloud manufacturing, but also software system integration (Lu, Frechette & Morris, 2016). As this is an area of research, the introduction of a reference architecture that connects elements from the smart manufacturing landscape to the lifecycles of the various smart manufacturing dimensions can help to provide structure in a complex environment.

1.2 Problem Formulation

The previous section describes the general academic challenge that exists in the fourth industrial revolution. This section describes the challenge in the more concrete context of Atos. Atos is an IT corporation that provides end-to-end business solutions to help their clients respond to the rapidly changing environment. They offer solutions for smart manufacturing to their clients. Atos recognizes the value of smart manufacturing and sees that it is at the core of digital transformation in manufacturing organizations. Therefore, Atos is already successfully implementing solutions to help their clients transition towards smart manufacturing. Nevertheless, they also acknowledge that the lack of standards makes it difficult to determine which combination of new technologies could most effectively contribute to a changing business model. A reference architecture for smart manufacturing will provide a "common source of reflection" in order to guide decisions in the path of digital transformation. Besides, a standard source of information a framework can also provide another opportunity for Atos. The framework can be used as a tool to help the client structure the status of their digital transformation. Without a reference architecture, it can be difficult and time-consuming to find the gaps within the companies’ smart manufacturing capabilities. By proposing a solution that fills these gaps and helps to raise the smart manufacturing system to the next level, Atos provides additional value to its clients.
Smart manufacturing can help to address many issues that currently play a role in manufacturing engineering, such as increased demand and greater variety (Helu, Morris, Jung, Lyons & Leong, 2015). To reach this goal, the manufacturing industry needs assistance from solution providers, such as Atos, to identify the right technologies and to ensure interoperability between new and existing systems to support the development of smart manufacturing (Helu et al., 2015). The application fields of smart manufacturing are numerous and so are the research issues restraining the development of smart manufacturing (Thoben et al., 2017). Structuring the knowledge that Atos has gathered as well as best practices from literature in a reference architecture can help to identify standardization opportunities, such that the full potential of the fourth industrial revolution can be reached (Helu et al., 2015).

The previous section illustrated the complexity of the smart manufacturing ecosystem but also emphasizes the potential of the new technologies for the manufacturing domain. However, due to the complexity and lack of standards to provide structure for the ecosystem, it becomes difficult to fulfill this potential. Therefore, the problem statement is defined as follows:

“The enterprises in the manufacturing industry do not have the knowledge to structure the technologies, activities, and capabilities of smart manufacturing, to reach its additional value.”

The problem defined here marks an issue for the entire manufacturing industry. Atos has many clients in this industry that face this problem and therefore Atos wants to provide a solution to their clients. The problem statement shows the relevance of this study and the need to provide the enterprises with a tool that contains the knowledge that gives them the opportunity to pursue smart manufacturing.

1.3 Research Goal

The goal of the research project is to design an information systems reference architecture that can support the development of smart manufacturing, by creating structure in the characteristics of smart manufacturing. According to Grefen (2016b), ”a reference architecture is a general design (abstract blueprint) of a structure for a specific class of information systems”. A reference architecture for smart manufacturing can help to resolve issues, such as the comparison of use cases, clarify the representation of smart manufacturing and the orchestration of workflows (Thoben et al., 2017). To date, smart manufacturing research focused on conceptual issues. To reach the full potential, smart manufacturing strategies must focus on each lifecycle step of a product such as design, operation and maintenance (Kang et al., 2016). Reference architectures are a required element for the application of technologies in each lifecycle step, to create consistency and standards (Kang et al., 2016). The goal of this research is to produce a solution, to solve the existing design problem. Based on this goal the design science paradigm is used to design an artifact as a solution. Therefore, it is important to state the objective of this research. Based on the problem introduction as well as the above-defined problem statement the research goal is defined as follows:

“The objective of this research is to develop an information systems reference architecture that supports the development of smart manufacturing.”

The deliverable of this study will be an artifact of the type model, as defined by the design science research terminology of Gregor and Hevner (2013), that shows a representation of the smart manufacturing characteristics, which helps enterprises to pursue and develop within the smart manufacturing paradigm.
Chapter 2

Research Methodology

This chapter describes the methodologies that are used to carry out the project and meet the above-defined research goal. The paradigms used to conduct this research are the problem solving cycle by van Aken, Berends and Van der Bij (2012) and the Design Science Research (DSR) paradigm by Gregor and Hevner (2013). Secondly, the research questions and the research method are defined. The final section of this chapter presents the research scope.

2.1 Research Paradigms

To conduct a design science research in a structured manner, van Aken et al. (2012) defined a problem solving cycle. This cycle consists of the following five steps (1) Problem definition, (2) Analysis & diagnosis, (3) Solution design, (4) Implementation, and (5) Evaluation, (Figure 2.1). These steps must be followed precisely throughout the research. Note that the first step of the cycle, the problem definition, is already provided in the previous section of this report.

Besides the problem solving cycle of van Aken et al. (2012) this study also uses the Design Science Research (DSR) paradigm, because the goal is to design an artifact as the solution for the problem described in Chapter 1. DSR is a well-known and fundamental paradigm in Information Systems research (Hevner, March, Park & Ram, 2004). The design framework, shown in Figure 2.2, focuses on the balance between relevance and rigor for the design within Information Systems research. The solution design, step 3 in the problem solving cycle of van Aken et al. (2012), corresponds to the design of an artifact in the DSR paradigm. According to Goldkuhl (as cited in Gregor and Hevner (2013)), an artifact is ‘a thing that has, or can be transformed into, material existence as an artificially made object’ (p.341). The DSR paradigm (original shown in Appendix A) is later extended by Hevner (2007) and Gregor and
Hevner (2013). The first extension includes three research cycles to balance the rigor and relevance of the conceptual design (Appendix A). The second extension is a knowledge contribution framework to position the conceptual design (Appendix A).

**Figure 2.2: Design Science Research Framework for this Research Project, based on (Hevner, March, Park & Ram, 2004)**

Gregor and Hevner (2013) position the DSR knowledge contribution framework, as a tool to position the developed artifact based on two scales: (1) Solution Maturity (i.e. relative to the already known solutions) and (2) Application Domain Maturity (i.e. problem context). The designed artifact in this study can be positioned within the improvement quadrant (Figure A.3), new solutions for known problems. More specifically, information from known I4.0 frameworks is used to provide more complete solutions to solve the defined problem.

Furthermore, the contribution of the artifact is also dependent on the maturity of knowledge (Gregor & Hevner, 2013). The scale for knowledge maturity ranges from level 1, developed artifacts for specific applications to level 3, a well-developed theory for general phenomena. The framework as artifact proposed in this study is designed for a more abstract problem and applicable in various situations. Therefore, the artifact is categorized as a level 2 contribution, a nascent design theory.

Finally, the DSR paradigm defines three fundamental research cycles, the rigor, relevance, and design cycle (Hevner, 2007). Each of these cycles has an important role in the successful solution design of an artifact. The rigor cycle ensures innovation by connecting the design activities to the existing knowledge base, the relevance cycle bridges the practical environment with the design activities and the design cycle iterates between design and evaluation using the requirements from the relevance cycle and information from the rigor cycle. The research cycles are put into the context of this project in the next section.

### 2.2 Research Questions and Research Approach

To reach the defined end-goal of this study, it is necessary to gather knowledge such that the artifact can be constructed. Therefore, the following research question is raised:

"*How can technologies, capabilities, and activities belonging to smart manufacturing be structured, such that it creates new values for the manufacturing industry?*

The defined question consists of two parts that must be answered separately. Firstly, the research will focus on structuring the various assets of smart manufacturing, to support organizations that want to integrate collaborative manufacturing systems. In addition, it is important that the constructed artifact, which in design science research is the answer to the research questions, creates value for manufacturers. Therefore, the framework must be evaluated in practice, to investigate if the framework indeed supports and clarifies the development of smart manufacturing.
To provide an answer to the above-defined question, it is necessary to answer several sub-questions, shown in Figure 2.3. This figure also introduces the research method as it visualizes the link between the problem solving cycle by van Aken et al. (2012), the DSR research cycles by Hevner (2007), and the sub-questions.

Figure 2.3 shows that RQ1 and RQ2 focus on the rigor cycle. This suggests that the main research is based on the knowledge base. However, as the design needs to be useful in practice, the research is also driven from relevance. This ensures that the eventual design is not only based on academic rigor but also include relevant aspects from the industry. Furthermore, the answers of RQ1 and RQ2 provide the results for the second step in the problem solving cycle of van Aken et al. (2012), analysis and diagnosis. The design cycle is an iteration between the actual development of a design artifact and the evaluation. Therefore, RQ3 is divided into three sub-questions, RQ3a, RQ3b and RQ3c. RQ3a provides the basis for the remainder of the design. The answer to this research question provides the dimensions that serve as an outline on which the characteristics can be positioned. RQ3b will be the result of the first actual development phase and after evaluation RQ3b is the result of the second iteration. The resulting artifact is the outcome of the solution design step in the problem solving cycle. Lastly the implementation, step 4, and evaluation, step 5 are answered by research questions 4 and 5. These research questions are mainly relevance driven and supported by the rigor cycle to ensure the link with the already existing knowledge base.

The fourth industrial revolution triggered many initiatives that are closely related to each other. These are terms such as Industry 4.0, smart manufacturing, CPS, Industrial Internet of Things (IIoT) and many more. As the concepts are all related, frameworks from other initiatives can provide an important insight to which elements are important for the Smart Manufacturing Framework (SMF). The Smart Manufacturing Framework is the artifact that results from this design science research and can be categorized as a model type contribution (Gregor & Hevner, 2013). The SMF is a higher-level representation including the models that form the smart manufacturing reference architecture discussed in Chapter 1. In other words, the reference architecture is an application of the smart manufacturing framework to a set of systems and is included in the SMF (Lin et al., 2017). Both terms are used in this document to define the artifact. The frameworks from other initiatives are all shortly discussed in Chapter 3, in order to determine the already existing knowledge base (RQ1). These frameworks all provide different insights and show a different approach. This makes it important to establish a common ground for the outline.
of the smart manufacturing reference architecture, which is also described in Chapter 3.

Once the necessary background is provided the architectures can be analyzed based on their characteristics, Chapter 4. For the actual design of the framework, it is important to know which elements are missing in the existing frameworks and which elements should be included in the reference architecture (RQ2). Based on the knowledge gathered from the analysis, an additional design rescope is made. The rescope ensures that the framework only reflects aspects that are relevant for smart manufacturing. Based on this rescope the appropriate dimensions for the outline of the framework can be determined (RQ3a). The design of the framework outline is described in Section 4.3.2. The positioning of the extracted characteristics on these dimensions is described in Section 4.3.3. The conceptual design provides an overview of the smart manufacturing aspects, extracted from the architectures and positioned based on the defined smart manufacturing dimensions (RQ3b). This shows a high-level unified framework that presents the TO-BE state of a smart manufacturing enterprise. RQ3a and RQ3b together form the design of the conceptual model, shown as one activity in Figure 2.4. Nevertheless, the framework is designed to support the development of smart manufacturing. This asks for an operational framework that visualizes how the TO-BE state can be achieved (RQ3b). The transformation of the conceptual model into an operational tool is discussed in Chapter 5. The separation between the conceptual and operational framework is shown in Figure 2.4.

The resulting Smart Manufacturing Framework is implemented by means of case studies in the manufacturing sector. The implementation is executed at two enterprises in the manufacturing industry. An implementation process is established and executed to evaluate if the framework is applicable within the manufacturing industry (RQ4). This method is also known as structural testing (Hevner et al., 2004). The implementation approach is the second artifact of this research and can be identified as a method type artifact (Gregor & Hevner, 2013). Successful execution of the implementation process results in a roadmap that shows the smart manufacturing development activities for a company. Furthermore, it provides insights into the usage of the framework as a tool for Atos. Both the implementation approach as well as the results from the case studies are discussed in Chapter 6.

The operational framework is evaluated during the case studies and described in Chapter 7. The evaluation method used is observational (Hevner et al., 2004), the use of the artifact is studied in a business environment. To establish the practical usefulness of the framework the participants of the case study are asked to evaluate the framework based on the relevance criteria defined by (Shrivastava, 1987).

Finally, conclusions and future research for both the conceptual and operational framework are discussed in Chapter 8. A complete overview of the research process is shown in Figure 2.4.
2.3 Research Scope

Since there is only a limited amount of time available to conduct the research, it is very important to determine the scope of the research to ensure its feasibility. Therefore, several decisions are made to adjust the magnitude of the research, to ensure the research load is manageable and the research does not become too broad. The decisions for scoping are described in this section.

Within the fourth industrial revolution, multiple initiatives are introduced by various organizations. The various initiatives are positioned in a Venn-diagram, shown in Figure 2.5. The Venn-diagram is designed previously to this research during the literature review, to provide some clarity and structure for the fourth industrial revolution (Brouns, 2019). The goal is not to create a framework that includes all the initiatives but to focus on one. The design of the reference architecture includes only elements that can be related to the smart manufacturing paradigm. The smart manufacturing initiative is less comprehensive than the Industry 4.0 initiative, as shown in Figure 2.5. The smart manufacturing paradigm does include the entire product lifecycle and mentions the value chain. According to Kang et al. (2016) a smart manufacturing framework should support every step of the product lifecycle. This means that the scope of the framework does include the entire product lifecycle, similar to the product lifecycle shown in Figure 1.2.

![Figure 2.5: Initiatives within the fourth industrial revolution (Brouns, 2019)](image)

Furthermore, the main research question shows another scoping decision, namely that the framework is designed to be applicable in the manufacturing industry. The manufacturing industry is closely related to the smart manufacturing paradigm. Although principles from smart manufacturing might also be applicable in other domains, the decision is made to focus on the manufacturing industry. This is also a relevant industry for Atos as many of their customers are manufacturers. Nevertheless, a framework for the manufacturing industry can still imply that the framework should also take care of organizational structures or blueprints for production facilities. These aspects are not included in the SMF. The framework focuses on the integration of information technology and operational technology and therefore be scoped to an information systems architecture. This scoping decision is also implied in RQ1.
Chapter 3

Theoretical Background

Before the design of the Smart Manufacturing Framework can start, it is essential to determine a common ground. In line with the objective of this research, the theoretical background first discusses the already existing architectures to establish the knowledge base. The goal of this research is to design an Information Systems Reference Architecture. Therefore, a formal definition of an information systems architecture is presented and the various types of architectures are discussed. Lastly, the AFIS framework is elaborated upon. The AFIS framework is an independent reference framework, focusing on connecting digital and physical processes and allows for the positioning of other reference architectures. The AFIS framework is used as the basis for the framework design.

3.1 Architectures in the fourth industrial revolution

Several industrial organizations, as well as standard development organizations, are creating reference architectures for the fourth industrial revolution. However, similar to the initiatives described in the previous chapter, each of these architectures has its own key concept and viewpoint on the fourth industrial revolution. Even though there are differences, most of the architectures take into account the following principles (Li et al., 2018):

- **Decomposition** means the description of multiple dimension within an architecture;
- **Focalization** the architectures focus on their core concepts and do not include all relevant elements of the fourth industrial revolution;
- **Strategic consistency** the architectures are based upon national manufacturing initiatives, such as smart manufacturing or Industry 4.0.

The architectures that are discussed in this section all results from the literature review prior to this thesis (Brouns, 2019). Only a summary of the results is given here, to create a basic understanding of the various architectures. A visualization of the frameworks and elaboration of the elements is provided in Appendix B. Once a more detailed understanding is deemed necessary for the design of the framework, this will be elaborated upon during that design step.

**The ISA-95 architecture** is a widely adopted framework for control system integration (American National Standard, 2005). The manufacturing pyramid, one of the most known visualizations of the standard, depicts a functional hierarchy model and plays an important role in the establishment of later frameworks. Although this architecture serves as a proper basis for system integration between the shop floor and enterprise level, it does not include the integration of Information Technology (IT) and Operational Technology (OT). According to (Lu, Riddick & Ivezic, 2016), the functionalities necessary to establish smart manufacturing are more advanced than the functions defined in ISA-95. Therefore, architectures that focus primarily on the fourth industrial revolution are required for a smooth implementation.

Lee, Bagheri and Kao (2015) propose the **5C architecture**, that provides a clear structure for implementing Cyber-Physical Systems. The architecture consists of five layers that all propose a step that will lead to the implementation of a CPS in a production facility. Nevertheless, the 5C architecture solely focuses on the vertical integration within a single production facility. It ignores any influences...
from the environment. Therefore, Jiang (2018) suggested an extension of the 5C architecture, the 8C architecture. By adding three additional facets, content, customer, and coalition, this architecture also includes the products lifecycle and the value chain. However, the architecture does not provide any information on how these facets should be integrated and applied to an enterprise.

The Reference Architecture Model Industry 4.0 (RAMI4.0) is built to achieve a common understanding between the various industries on standards and use cases for I4.0. Three dimensions that are all relevant for I4.0 display these fundamental aspects. The framework contains layers, the lifecycle and hierarchy levels (VDI/VDE, 2015). The three-dimensional structure of the framework enables the positioning of I4.0 standards and helps the identification in overlap and gaps. This approach provides an overview of the already existing and missing standards in the paradigm of I4.0. However, it does not provide guidelines on how to establish I4.0 aspects in an enterprise. Furthermore, the integration of the various standards created inconsistencies in terms and there is a lack of proper clarification (Frysak, Kaar & Stary, 2018).

The National Institute of Standards and Technology (NIST) constructed the smart manufacturing ecosystem (SME). The SME enhances a broad scope of manufacturing systems including product, production, and business. These three dimensions encompass the manufacturing pyramid, an applied version of the ISA-95 standard (Lu, Frechette & Morris, 2016). The ecosystem provides a complete overview of the various lifecycles and the vertical integration by the manufacturing pyramid. The standardization of the framework mainly focuses on software applications and the information flows that can support the lifecycle processes. Nevertheless, the focus on software applications results in a lack of key technology identifications and implications. This leads to limited improvement in the information system infrastructure as concepts such as cloud computing and IoT are omitted (Li et al., 2018).

The Industrial Internet Reference Architecture (IIRA) is designed by the Industrial Internet Consortium, to support the development of Industrial Internet of Things systems (Lin et al., 2017). The IIRA consists of four viewpoints that show the key aspects of the reference architecture. Each viewpoint includes its own domains, processes, information flows and techniques to support the development of an IIoT system. Even though the architecture itself is not sufficient to fully implement an IIoT system it does serve as a good starting point. The architecture is applicable to various numbers of industries due to its high abstraction level. Furthermore, the lifecycle for both the design and implementation of an IIoT system is included in the architecture (Lin et al., 2017).

The architecture proposed by Wan et al. (2016) is designed to solve the challenge of information sharing within the field of IIoT. The Software-defined IIoT architecture (SD-IIoT) visualizes data sharing across three layers and based on four different devices. It emphasizes the service-oriented approach by implementing three data related services. Clear communication protocols to transmit data from the physical layers to the cloud are important aspects. Only in the layer where the cloud is controlled data can be analyzed and value can be created (Wan et al., 2016). Nevertheless, this framework does not include any guidance towards the development of IIoT systems, nor does it include specific standards or protocols for data transmission and information sharing. The framework mainly suggests that data must be transferred from a physical asset to a cloud control or other platform.

The Internet of Things Architectural Reference Framework (IoT-ARF) is designed by the IoT-A project (Bauer, Boussard, Lucent, Bui & Carrez, 2013). The IoT-ARF presents a functional overview of the various components in the IoT paradigm. The framework does not propose any interaction among the various components as this can vary based on design decisions. The functional domain model includes the main assets that must be considered when deploying IoT. The entire framework is more elaborated than only the functional view and contains among others an information and communication model.

To identify which elements are relevant for the SMF and what is still missing a more thorough analysis of the framework is conducted in Section 4.1.
3.2 Information Systems Architecture

In general, an architecture is about providing structure. It serves as a blueprint for the design of complex systems (Grefen, 2016b). In a complex environment such as smart manufacturing, an architecture can be extremely useful to guide the implementation of smart manufacturing systems. Furthermore, an architecture can serve as an instrument to support agility within an organization (Grefen, 2016b). One of the goals of smart manufacturing is to improve the agility of the production process (Lu, Riddick & Ivezic, 2016). This means that an organization should be able to respond to the technology push and not only to the requirements pull. An architecture can be a pivot between the business and organization requirements (B&O) on top and technology (T) on the bottom, shown in Figure 3.1. (Grefen, 2016b).

The goal of this thesis, as is described in Chapter 1, is to develop an information systems reference architecture. A reference architecture is used for the design of concrete architectures. Therefore, it should serve the design and development of systems in a variety of contexts and projects (Angelov, Grefen & Greeffhorst, 2012). According to Bass, Clements and Kazman (2003) a reference architecture is defined as "a reference model mapped onto software elements (that cooperatively implement the functionality defined in the reference model) and the data flows between them", where the reference model is "a division of functionality together with data flow between the pieces". The border between reference architectures and concrete architectures can be rather vague because a concrete architecture can be used in multiple contexts without it being a reference architecture. Therefore, the level of abstraction in reference architectures is higher than for concrete architectures (Angelov et al., 2012). The standard architecture can be placed in between, which provides structure for specific architectures in an organization (Grefen, 2016b). The abstraction level, the level of detail, is one of the dimensions on the three-dimensional design cube that provides context for the design process, Figure 3.2. The other two dimensions are aggregation, number of elements, and realization often represented using the BOAT description (Grefen, 2016b). For the design of the framework, the 3D design cube is used to determine the right levels in the dimensions.

Figure 3.1: Architecture as a connector of Business and Technology taken from (Grefen, 2016b)

Figure 3.2: Three-dimensional design cube (Grefen, 2016b)
3.3 The Advanced Flexible Information System Framework

The Advanced Flexible Information Systems (AFIS) framework, shown in Figure 3.3, is created to properly position systems that connect the physical and administrative processes. The integration of these two processes is rather difficult, so creating a standard such that similar systems can be compared and analyzed can support this integration. The conceptual framework, designed by Grefen, Eshuis, Turetken and Vanderfeesten (2018), consists of four layers that represent the abstraction level, where the physical layer represents the lowest level and the business layer the highest. At the physical layer the work is executed. The commands and events of the physical layer are processed in the event layer. The process layer provides a control flow between the tasks of the event layer. Eventually, the business layer puts the process into a business context and is considered with the decisions making on a strategic, tactical and operational level. Furthermore, the framework contains two perspectives. The design time perspective that includes designing and analyzing the models. The second perspective is the execution time perspective that executes the models and collects the real-time output. The layers and perspectives together form the main structure of the framework. Within that structure, data flows and functionalities are positioned. The data flows are divided in a descriptive and prescriptive flow. These flows support the flexibility that is needed for future information systems. Lastly, the framework shows seven different functionalities. The functionalities show the key capabilities that a framework should possess when operating in an agile environment. Among others, the functionalities hold, data gathering, data analysis, and model design. The outline of the AFIS framework serves as a proper starting point for the design of the SMF, as it includes the connection between physical and administrative process, similar to smart manufacturing, in the abstraction layers and perspectives.

Figure 3.3: AFIS framework
Chapter 4

Conceptual Design

The previous chapter discussed the already existing reference architectures. In this chapter these architectures are further analyzed. Thereafter, the design principles are elaborated upon, such that the scope of the design is clear. Lastly, the design approach is presented, including the visualization of the conceptual framework.

4.1 Architecture Analysis

The result of the literature review shows that a variety of architectures for the Industry 4.0 paradigm is available. Each of these architectures has its own viewpoint and scope, which makes integration a challenge. In order to determine the relevant aspects of these architectures for the smart manufacturing framework, a thorough analysis is conducted. First, the architectures are analyzed and categorized based on a framework for evaluating software reference architectures. This provides insights on the type of architecture and the congruence of the architectures, if they fulfill all the criteria. The second analysis is based on the characteristics for the fourth industrial revolution, based on Li et al. (2018).

The architectures that are analyzed in this section are shown in Figure 4.1 and result from the literature review conducted prior to this master thesis (Brouns, 2019). A few changes have been made compared to those results, both the ISA-95 and the extended 5C architecture are excluded from the analysis. The ISA-95 framework is not taken into account as it is not a specific framework for the fourth industrial revolution, rather a well-known standard for manufacturing as a whole. Furthermore, the extension of the 5C architecture is rather limited and does not add a significant change to the basic 5C architecture. An overview of the analyzed frameworks including a short description is provided in Appendix B.

The architectures shown in Figure 4.1 are categorized based on the various initiatives within the fourth
industrial revolution. The 5C architecture only supports one of the elements for Smart Manufacturing, the Smart Factory, while the other architectures have a main interest in the implementation of the Internet of Things. Although IoT is one of the key enabling technologies of smart manufacturing, it is only one of the many aspects that must be addressed. There are only two architectures that include all the requirements for smart manufacturing, RAMI 4.0 and SME. Nevertheless, it is still worthwhile to analyze these architectures as they all contain elements that are relevant for the smart manufacturing paradigm.

4.1.1 Framework for congruent reference architectures

According to Angelov et al. (2012) software reference architectures are influenced by three dimensions, the application context, goals, and design. Based on these dimensions a framework is created to evaluate the level of congruence for reference architectures. An architecture is considered congruent if the above dimensions are aligned, Figure 4.2a. There are multiple types of reference architectures. Therefore, first a classification must be made before the congruence level of an architecture can be evaluated. The classification is based on the three dimensions discussed above. Each of these dimensions is divided into sub-dimensions, which are set by means of interrogatives. This leads to a total of eight questions that must be answered, such that the reference architectures can be categorized into five types. Appendix C shows an overview of the sub-dimensions and criteria, Table C.1, and the corresponding reference architecture types, Table C.2.

Figure 4.2: Analysis of a reference architecture (Angelov, Grefen & Greefhorst, 2012)

The following approach is used for the analysis of the architectures, as is recommended by Angelov et al. (2012): (1) Identify the dimension values for the architecture, (2) Map these values on the types and classify the architecture, (3) Analyze the architecture, a visualization of the process is shown in Figure 4.2b. Executing this process, results in the categorization of the reference architectures and shows the similarities between the reference architecture type and the actual reference architecture.

The identification of the dimension values is the first step for analyzing the reference architectures. Based on the questions one or more of the corresponding criteria were selected as a match for the reference architecture. An overview of the answers for each reference architecture is given in Appendix C Table C.3. A choice is made to classify all architectures as classical architecture, instead of a preliminary architecture. Categorizing an architecture as preliminary limits the possibilities for the analysis and would categorize all architectures as type 5, a preliminary, facilitation architecture. Even though the architectures are designed for solutions that are still in a development phase, such as industrial internet and smart manufacturing, many of the aspects in the architectures are known solutions. To obtain the most value of this analysis, the architectures are classified as classical. Another interesting observation is that all of the architectures are designed to be applicable to multiple organizations and are designed by independent organizations. A differentiation between the architectures is made based on the goal for which the architecture is designed. Only two of the architectures, RAMI 4.0 and SME, are primarily designed for standardization purposes. The remainder of the architectures is designed with the goal to implement certain technologies and functionalities.
Based on the characteristics that were determined in the first step, the architectures are classified based on the types. RAMI 4.0 and SME are classified as type 1 since both are classical reference architectures, designed for multiple organizations and have a standardization purpose. The other architectures have the same characteristics for the first two aspects. However, their goal is facilitation hence, these architectures are classified as type 3.

The analysis of the architectures is shown in Table 4.1. Each reference architecture type has corresponding characteristics, these are compared with the determined dimension values from step 1. In case the architecture values correspond to the type an X is denoted, when there are some deviations \( \approx \), and "-" when there is no match. The results show that none of the reference architectures is congruent, although the IoT-ARF is almost congruent except for the, "who" sub-dimension. The deviations do not imply that the reference architectures are wrong or cannot serve their purpose. Some of the deviations have a bigger impact than others.

Based on the analysis it can be concluded that none of the architectures designed for the fourth industrial revolution are congruent. Still these architectures can provide critical insights in both standardization and facilitation purposes. Furthermore, the two architectures that comprise all functionalities of the smart manufacturing paradigm, RAMI 4.0 and SME, are both categorized as standardization frameworks. This shows a gap, as there is also a need for facilitation architectures within this paradigm. Most research is still conceptual and there is only a limited success of real-life implementations (Kang et al., 2016), which provides the opportunity for an architecture that has as main purpose the development of smart manufacturing.

### 4.1.2 Evaluation by Characteristics of the 4th Industrial Revolution

Each of the reference architectures is developed by another organization, containing its own viewpoint and characteristics that comply with that viewpoint to fulfill specific requirements in the fourth industrial revolution (Takahashi, Ogata & Nonaka, 2017). In order to create a framework that contains all the relevant aspects of smart manufacturing, it is important to create an overview of the characteristics that are present in each architecture. The characteristics introduced by (Li et al., 2018) serve as a basis for the analysis. The most relevant characteristics are categorized according to the four aspects of the BOAT framework: Business, Organization, Architecture, and Technology (Grefen, 2016b). Characteristics such as new materials and new energy are excluded from this analysis, as they are less relevant for a software-oriented architecture. Furthermore, some of the characteristics that Li et al. (2018) identified show a high-level of similarities. For example the characteristics organization scope and system hierarchy, both illustrate an abstraction level within the organization. Therefore, the organization scope is discarded and system hierarchy is included in the analysis, as this showed a close relationship with the existing RAMI 4.0 framework. The results of the analysis are shown in Table 4.2. Note that the row for Manufacturing technology is empty. None of the architectures includes new manufacturing techniques, such as 3D-print or robotics.

The analysis shows that none of the architectures cover all relevant characteristics and there is the need for a framework that supports the implementation of smart manufacturing on a Business, Organization, Architecture and Technology level. Therefore integration of the characteristics from different architectures is necessary to support the development of smart manufacturing. Both RAMI 4.0 and SME include many of the aspects of the Business, Organizations and Architecture level. Combining elements from these two architectures and adding technology characteristics of for example IoT-ARF, would already create a more complete framework.
### 4.2 Establishing the Design Principles

In the second chapter of this report an initial research scope is provided. The initial scope limited the research to the smart manufacturing paradigm and to the manufacturing industry. Furthermore, it presented that the framework should only contain information system aspects. This section further refines the initial scope. Therefore this section provides a concrete definition for smart manufacturing. Furthermore, aspects from the BOAT and AFIS framework described in Chapter 3 are used to provide a clear goal and starting point for the design.

First, it is necessary to provide a definition of smart manufacturing that is used as a basis for the design of the Smart Manufacturing Framework. The goal of smart manufacturing is to improve quality, flexibility, productivity, and sustainability by digitizing the manufacturing domain (Lu, Frechette & Morris, 2016). This can be achieved by the integration of physical and digital business processes. The physical encloses the actual activities on the shop floor, the production process. The digital embrace the administrative process, such as customer orders and product descriptions. This goal is also included in the definition of smart manufacturing that is used as a foundation for the development of the framework (Kusiak, 2018)

“**Fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network and in customer needs**”

The definition above includes the broad scope of smart manufacturing stretching beyond a single factory throughout the life cycle of a product and its supply chain. This approach for smart manufacturing is closely related to the approach of Industry 4.0. According to Kamble, Gunasekaran and Gawankar (2018) vertical integration is necessary to enable the above-described requirements for a single factory. Horizontal integration is required to support the entire supply chain network. Lastly, the combination of the two leads to the end to end digital integration, to fulfill the customers’ needs and support the product along the lifecycle. These three features together enable the smart manufacturing paradigm.

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#### Table 4.2: Analysis based on 4th Industrial Revolution Characteristics

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Characteristic</th>
<th>5C</th>
<th>RAMI</th>
<th>SME</th>
<th>IIoT</th>
<th>IoT-ARF</th>
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<td>Product Lifecycle</td>
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<td>X</td>
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<td></td>
<td>Value Chain</td>
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<tr>
<td>Organization</td>
<td>Performance</td>
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<td>X</td>
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<tr>
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<td>Functional Layers</td>
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<td>X</td>
<td>X</td>
<td></td>
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<tr>
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<td>~</td>
<td>X</td>
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<tr>
<td></td>
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<td>X</td>
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<tr>
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<td>Data Storage/Processing</td>
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<td>Virtual (AR/VR)</td>
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<tr>
<td></td>
<td>Communication</td>
<td>~</td>
<td>X</td>
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</table>

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**Figure 4.3: The four aspects of smart manufacturing, adapted from Wang, Wan, Li and Zhang (2016).**
Besides these three aspects an equally important but often forgotten aspect is the use of new technologies. The importance of this aspect is emphasized by the following statement, Moeuf et al. (2018) claims each definition for Industry 4.0 includes the use of new technologies. The same holds for the smart manufacturing paradigm, where IoT is considered as one of the main enablers (Yao et al., 2017). For this reason, the technology aspect should be included as the fourth feature that enables the smart manufacturing paradigm. The scope of smart manufacturing is visualized in Figure 4.3.

It is possible to translate these aspects into activities and divisions within an enterprise. For a manufacturer, the term production is more tangible and more used, than vertical integration of a facility. Porter’s value chain is a well-known and often used method to show the various aspects of an enterprise (Porter, Millar et al., 1985). Figure 4.4, shows the functions that are in scope based on Porter’s value chain. The green functions represent the scope, the grey functions have a direct link to the scope and the red functions are out of scope.

Second, the design process for the framework focuses mainly on the architecture level within the realization dimension, the A within the BOAT framework. This decision is made due to the limited time of the project. In addition, the architecture dimension is expected to be the most relevant, as the positioning of software systems and their connectivity is an important part of smart manufacturing. Nevertheless, as the goal is to design a complete reference architecture, aspects from the other levels within the BOAT framework will be partially included in the model and receive attention.

Third, as a starting point for the design of the SMF, an independent reference architecture is used. The framework for Advanced Flexible Information Systems is already introduced in Section 3.3 and serves as a good starting point. It is designed to position already existing architectures and can, therefore, be used as a tool in the design process. It is specifically designed to position systems that connect the physical and administrative processes. Smart manufacturing is also an integration of a physical production processes and administrative processes such as design and order systems. For this reason, the AFIS framework is expected to be a useful tool to map the characteristics of smart manufacturing.

4.3 Design Approach

In this section of the report, the design of the conceptual framework is described. First, the use of the 3D design cube is discussed. Second, the AFIS framework is adapted to the fourth industrial revolution. Lastly, the conceptual framework is presented.

4.3.1 The Three-dimensional Design Cube

As was mentioned in Section 3.2, the three dimensional (3D) design cube of Grefen (2016b) is used to determine the right dimensions for the framework design. Figure 4.5 visualizes the three-dimensional design cube in the 3D version (left) and 2D (right). In the 2D version the colored block depicts the...
architecture model at a specific level of aggregation, abstraction and realization (Grefen, 2016b).

During the design of an architecture, a design space is traversed (Grefen, 2016b). The 3D design cube provides a design space using three dimensions, aggregation, abstraction, and realization. The aggregation dimension determines the level of detail, abstraction is the level of concreteness and the realization dimension follows the BOAT-framework.

The number of levels within every dimension of the design cube can be specified for every project. This project uses the 3D cube consisting of 3x4x4=48 cells, as visualized in Figure 4.5. Due to time restrictions, it is not possible to traverse the design cube. Traversing the design cube would lead to a new architecture design for each of the steps and drastically increases the number of models. Therefore, the design is positioned at one cell within the cube. The design of the Smart Manufacturing Framework is positioned on aggregation level 3, i.e. main structure contains components, abstraction level 2, i.e. specific system types and the architecture level of realization. The levels are described more specifically in Appendix D.

**4.3.2 RAMIfication of the AFIS framework**

The AFIS framework is designed to position any flexible information system and is not specific for the fourth industrial revolution. The focus of this research is the manufacturing domain. Therefore, the outline of the framework should incorporate aspects that can easily be related to this domain. Designing the basis of the framework based on principles from the manufacturing industry makes it recognizable for the intended end-users. Furthermore, it ensures that the smart manufacturing capabilities are placed within the right context.

According to Kang et al. (2016), a Smart Manufacturing Framework should support all the steps in the product lifecycle process. This holds that the application of systems and technologies is necessary for each of the lifecycle steps and interoperability of the heterogeneous systems is required. Supporting the product lifecycle is part of the design scope and matches with one of the four key aspects of smart manufacturing, End-to-End Integration. There are many variations of product lifecycle management, varying in the number of lifecycle phases and all displaying different terms (Kiritsis, 2011; Stark, 2015; Subrahmanian, Rachuri, Fenves, Foufou & Sriram, 2005).

The product lifecycles are included in both the RAMI4.0 and SME architectures. The lifecycle of SME is a bit more elaborated and consists of 6 phases, where the RAMI4.0 lifecycle only consists of 4 phases. The Smart Manufacturing Framework will eventually be used as a tool. Therefore, it should be easy to use and the elements must be recognizable. The goal of the framework is to be generic and applicable to any production enterprise. Nevertheless, the tool should mainly serve Atos’ clients, so it should be in line with the best practices Atos already uses. A visualization of one of these best practices is provided in Figure 4.6. The product lifecycle steps defined by Atos are only three, design, make and use/service.

An overview of the product lifecycles is provided in Figure 4.7. The figure positions the phases of the various lifecycles relative to each other. The lifecycle at the bottom visualizes the phases that are included in the Smart Manufacturing Framework. The decision is made to integrate the RAMI4.0 and Atos lifecycles to create a new lifecycle. This led to a lifecycle that is still generic, so not just specifically
designed for Atos, but has a strong connection with the best practice of Atos. This makes it a recognizable lifecycle for the intended users, as well as any manufacturing company.

The most important change in the lifecycle is to replace the design phase with the development phase. The development phase is more comprehensive and also includes activities after the initial design of the product, such as production engineering and version control. After evaluating the lifecycle with multiple employees at Atos it was deemed unnecessary to split the development phase. This would be harmful to the accurate positioning of the smart manufacturing characteristics and the readability of the framework. The production and usage/service phase are both similar to the phases in the other lifecycles. The production phase considers making the actual product and the usage/service phase includes services and activities for the product in use. The recycling phase that is shown in SME is excluded from the lifecycle, as it does not provide enough value for the lifecycle dimension and the placement of smart manufacturing capabilities.

According to Li et al. (2018) there are two suitable dimensions for a Smart Manufacturing Framework. The lifecycle, as was just discussed, and enterprise hierarchy levels. The enterprise hierarchy levels are also part of the RAMI4.0 framework and describe a certain level of abstraction. The hierarchy levels in RAMI4.0 follow the IEC 62264 and IEC 61512 standards, also known as the equipment hierarchy model from the ISA-95 and ISA-88 standards. The two hierarchy dimensions are shown in Figure 4.8.

The RAMI levels are based on the ISA-95 and ISA-88 standards, but also show quite some differences. For the design of the Smart Manufacturing Framework, the two models are combined. However, the hierarchy equipment model is used as a basis, as this standard is already well established and often evaluated. An important note is that the visualization shown in Figure 4.8b, is the integrated view of both the ISA-88 and ISA-95 model. The ISA-88 standard focuses on batch control production, while the ISA-95 standard also includes, continuous production, discrete production, and storage. The main
focus of the framework is the discrete manufacturing industry. Therefore, the elements from the ISA-88 standard, equipment module and control module, are out of scope.

The work cell is the lowest hierarchy level. The equipment in a factory can be positioned here to execute simple activities, for example, the sawing machine or painting station. Integration of the work cells creates a production line. A production line can produce multiple items in a row and execute multiple functionalities, for example, an assembly line. A site is the actual physical factory and involves production lines and cells to produce a (half)-product. The activities for a site include production planning and scheduling, which are higher level activities than the actual production itself. Note that the area is not included. Due to the small difference between area and site, it might become unclear where to position some of the smart manufacturing characteristics. On top of the site is the enterprise, the highest hierarchy level in the ISA-95 model. An enterprise can consist of multiple production facilities, sites, and strategic decisions are made on this level, such as what product will be manufactured where. RAMI 4.0 added another level on top of the enterprise, connected world, to illustrate that I4.0 activities stretch beyond a single enterprise. The same holds for smart manufacturing. Therefore, the decision is made to add a hierarchy level on top of the enterprise level. The connected world is a bit vague and includes a large scope. This large scope is not necessary as an enterprise does not have to be connected to the entire world. It is important for an enterprise to stay connected with their own network of suppliers and customers (Carvalho, Chaim, Cazarini & Gerolamo, 2018). Thus the network is considered to be the highest hierarchy level. RAMI 4.0 also connects two hierarchy levels to the bottom of the ISA-95 model, the product and field device levels. Both are not included in the hierarchy levels of the Smart Manufacturing Framework. The field device level, includes for example smart sensors. The assumption is made that these sensors are either part of the equipment in the work cell layer or part of a product. The product layer is also omitted because the product requires its own lifecycle. According to Frysak et al. (2018), it is considered a pitfall when the product is also an integral part of the plant, thus it is not included as a separate hierarchy level. The visualization of the hierarchy levels is presented in Figure 4.9.

The hierarchy and lifecycle dimension serve as the outline for the new, smart manufacturing oriented, AFIS Framework. Mapping those two dimensions on to the AFIS framework creates the basis for the SMF. This mapping is visualized in Figure 4.10 and the end result is shown in Figure 4.10b. Originally, the AFIS framework consists of a design and execution time perspective. The design perspective is replaced by the development phase, that holds the same functionalities, such as analysis by simulation and the design functionality. The execution perspective is divided into two phases, the production phase
CHAPTER 4. CONCEPTUAL DESIGN

(a) Hierarchy and Lifecycle Dimensions

(b) Adapted AFIS framework

Figure 4.10: RAMification of the AFIS framework

and the usage/service phase. The production phase holds very similar functionalities to the execution perspective, such as gathering the data from the shop floor, adjusting machines and planning based on the analysis and the actual control. The usage/service phase is a bit more difficult to define. In this phase, real-time data is gathered from the product in use, as well as the gathering of customer related data and customer orders. The latter does not have to be real time. The abstraction layers of AFIS are replaced by the hierarchy dimension. The hierarchy dimension also considers a certain level of abstraction. The lowest abstraction level, the work cell, executes the physical work and is more hardware-oriented. One level higher the events from the work cell layer are processed in the context of a production line. On the highest level of abstraction information is processed in the context of a collaborative value network, such that they relate to the business goals the network determined. A mapping of the AFIS abstraction layers and the hierarchy dimension of the SMF is provided in Table 4.3.

Table 4.3: Mapping AFIS abstraction layers and SMF Hierarchy Dimension

<table>
<thead>
<tr>
<th>AFIS Abstraction Layers</th>
<th>SMF Hierarchy Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td><strong>Layer</strong></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Relate process effects to a business context</td>
<td>Business</td>
</tr>
<tr>
<td>Creating a control flow between tasks</td>
<td>Process</td>
</tr>
<tr>
<td>Processing activities of Physical Layer</td>
<td>Event</td>
</tr>
<tr>
<td>Physical assets gather data and execute tasks</td>
<td>Physical</td>
</tr>
</tbody>
</table>

Before the smart manufacturing characteristics can be positioned on the framework, it is necessary to connect the hierarchy levels and the lifecycle phases. The hierarchy levels are based on a manufacturing standard, which relates closest to the production phase. Nevertheless, it must be possible to accurately position elements on any level in any phase. Therefore, for each cell the meaning is defined, based on the relationship between the hierarchy and lifecycle dimension. Providing a common guideline for the mapping helps to position the artifacts correctly. For the cells in the usage phase on site and production line level, no definition is provided. The assumption is made that the levels and phase hold no clear relation, mainly because no elements were found in real-life scenarios that fit these cells. In the production phase at the work-cell level the sensors are attached to the machines and data about the physical process is generated. A similar approach for the product in use is used, the sensors are included in the product and data is generated from the product. The relations are described in Figure 4.11.
### 4.3.3 Conceptual framework

Now the AFIS framework is adapted to the fourth industrial revolution, the smart manufacturing characteristics can be mapped on the new version of the AFIS framework, AFIS/4IR. Therefore, the main information system characteristics of the evaluated architectures are extracted and positioned on AFIS/4IR. A visualization of the positioning is shown in Figure 4.12. The various shapes and colors show to which architecture the characteristic belongs, displayed in the legend at the bottom of the figure.

All the extracted elements can be related to one of the I4.0 characteristics discussed in Table 4.2. Aspects of the analyzed architectures that could not be related, were not taken into consideration for the positioning. Some of the elements were easier to position than others, mainly due to the concreteness of the element or the positioning within its own architecture. For example, the software components extracted from the Smart Manufacturing Ecosystem are rather concrete and already positioned along a product lifecycle. Additionally, the elements only must be positioned on the hierarchy levels. The equipment hierarchy can be linked to the functional hierarchy of ISA-95. The functional hierarchy divides elements such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), and Supervisory Control and Data Acquisition (SCADA), based on their functionalities (Erasmus, Vanderfeesten, Traganos & Grefen, 2018). A direct mapping can be made with the equipment hierarchy. Therefore, the manufacturing pyramid can be recognized within the production phase, field device for sensing and manipulating, SCADA for Control, Manufacturing Operations Management (MOM) for workflow control, and ERP for enterprise scheduling. The Product Lifecycle Management (PLM) system is considered to be at a similar hierarchy level as an ERP system, as it considers a long term focus. Furthermore, it stretches along the entire product lifecycle, according to the visualization of the SME (Lu, Frechette & Morris, 2016). The other elements of the SME are positioned using a similar approach.

The identification of relevant elements in the Industrial Internet Reference Architecture, was more difficult, due to the high abstraction level and a high-level description of viewpoints (Lin et al., 2017). Therefore, only four relevant elements could be extracted. These elements are all positioned within the production phase, as that is considered the main application domain for the Industrial Internet. The business view and usage view are both high-level viewpoints, directly visible in the IIRA. The business viewpoint includes business-oriented concerns and is therefore positioned on an enterprise level. The usage view considers the actual activities to solve those business concerns and is positioned one level lower in the hierarchy. Both the operations/information and control elements are extracted from the functional domain model, one aggregation level higher than the functional viewpoint. The control functionality enables the sensing and actuation of the physical system, similarly to the field device, and is positioned on the work cell level. The operations and information domain provide the data collection from various business applications, data modeling, data analytics and provides the user interfaces. These

---

#### Figure 4.12: Mapping Hierarchy Dimension and Product Lifecycle

<table>
<thead>
<tr>
<th>Network</th>
<th>Development</th>
<th>Production</th>
<th>Usage/Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrating Supplier Services</td>
<td>Integrating Manufacturing Services</td>
<td>Integrating Customer Services</td>
<td></td>
</tr>
<tr>
<td>Enterprise</td>
<td>Managing multiple product designs</td>
<td>Managing production multiple products</td>
<td>Managing Customer Data</td>
</tr>
<tr>
<td>SIM</td>
<td>Design of the product</td>
<td>Production of the product</td>
<td>X</td>
</tr>
<tr>
<td>Integration of Product components</td>
<td>Combined equipment producing product parts</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Work Cell</td>
<td>Design of product components</td>
<td>Equipment handling product components</td>
<td>Monitoring product in use</td>
</tr>
</tbody>
</table>
activities go beyond enterprise borders, thus the operations and information domain are positioned on the network level.

Figure 4.12: Mapping of smart manufacturing characteristics on AFIS framework

The main focus of the 5C architecture is, similarly to the IIRA, within the production phase, as it is designed to develop a CPS within a factory (Lee et al., 2015). However, some of the high-level elements can also be related to the entire lifecycle such as data conversion and simulation. Therefore, these elements are stretched across the lifecycle and marked at the right side of the framework, to show that they affect the entire hierarchy level. The sensor network in the smart connection level can operate on the shop floor, but also on a product in the usage/service phase. The configuration level contains the self-adjust functionality of machines and stretches from enterprise to work cell. Decisions made on the enterprise level automatically affect the machines and systems on a lower level. The conversion level executes component based, low-level analytics on a production line level. The cyber level is positioned one level higher as it concerns the clustering of the machine data. Lastly, diagnostics and decision making happens with the cognition level, which is an enterprise-wide functionality.

The Software-Defined IIoT architecture focuses mainly on the integration between the physical, control and application layer using industrial bus or cloud, either private or public (Wan et al., 2016). The cloud is positioned on a network level, to improve the availability of services beyond the enterprise and ensure standardization. The BUS is used to connect the systems enterprise-wide.

The IoT-ARF provides a complete overview of IoT implementation, but this report only considers the functional model (Bauer et al., 2013). Mainly the service-oriented aspects are valuable for the positioning within the SMF. According to Vandermerwe and Rada (1988) services become increasingly important for industries and a rising number of companies shifted their focus from goods to services. Services are also considered to be the central factor of economic growth, which would clarify the interest of companies (Ehret & Wirtz, 2010). The IoT-ARF uses an IoT communication layer on the work-cell level for the connectivity between sensors and actuators. The process management and execution are positioned on a site level. The notion that the enterprise should be a service organization is stretching across the product lifecycle. And lastly the IoT service is a service that is offered towards the customer, thus positioned on a network level in the usage/service phase.

The positioning of the smart manufacturing characteristics provides an overview of the aspects from various architectures. Nevertheless, it still displays a scattered ecosystem and might also cause confusion due to the high amount of elements. To overcome this a high-level overview is presented that contains the main functionalities within the smart manufacturing paradigm, Figure 4.13. This high-level overview presents the goal of an enterprise that wants to become a smart manufacturing enterprise. The digital product twin can improve the process of product development, based on virtual and physical data. This can not only lead to improvements in the product development phase, but along the product
lifecycle (Tao et al., 2018). The smart factory is a core concept within smart manufacturing and is supported by the Internet of Things and CPS (Yao et al., 2017). The goal of the smart factory is to increase the intelligence and flexibility of a plant to become more cost-effective. The integration of machines products and resources should improve the self-optimization of the production process and meet customer requirements by enabling mass customization (Douaioui et al., 2018). The connected customer is necessary for the enterprise to quickly respond to the fast changing customer demands and to allow for mass customization. This is all coordinated, by the integrated enterprise information systems along the product lifecycle and enabled by a service-oriented business. On a network level smart manufacturing strives for an integrated supply chain and an agile collaborative network (Santos, Mehrsai, Barros, Araújo & Ares, 2017).

The conceptual framework visualized in Figure 4.12 provides an integrated overview of the important characteristics within the smart manufacturing paradigm. The characteristics are mapped on an independent framework using two relevant axes. The mapping on an independent framework, shows a unified model, including elements from various viewpoint. A unified model for smart manufacturing should benefit users with a central and complete value, instead of the specific functionalities each individual reference architecture now offers (Takahashi et al., 2017). It indicates which elements should be present within an enterprise that pursues a smart manufacturing journey. Furthermore, it shows that enterprise information systems provide an important basis for the success of smart manufacturing, while this is often not considered to be a key aspect like IoT and CPS (Pereira & Romero, 2017; Thoben et al., 2017).

An important shortcoming of this framework is the low level of operational capabilities. The framework only provides a complete picture of all the elements that are needed for smart manufacturing, as well as a high-level overview of the ideal situation. It can not directly be used as a tool by Atos to show clients the opportunities that the smart manufacturing paradigm can offer. Furthermore, it does not include a guideline how an enterprise can reach the ideal situation. This is especially important, as the initial goal of the framework is to support the development of smart manufacturing. For this reason, this conceptual framework design should be transformed into an operational framework that contains activities and can be used to design a roadmap to ensure the feasibility of the smart manufacturing journey.
Chapter 5

Operational Framework Design

In this chapter the conceptual framework as introduced in the previous chapter is transformed into an operational framework. The conceptual framework is here referred to as the \( \alpha \)-version, and the operational framework as the \( \beta \)-version. The \( \alpha \) and \( \beta \) approach is based upon a well-known testing strategy (Sawant, Bari & Chawan, 2012). The \( \alpha \)-model is used for in-house testing to examine whether the main outline was useful and the characteristics were recognizable. During meetings with possible users, the outline of the conceptual framework proved to be useful, but the overall approach appeared to be too conceptual. The decision is made to create a \( \beta \)-version that is operational and can be used in the industry. The \( \beta \)-version is an extension of the \( \alpha \)-version. In other words, the outline of the \( \alpha \)-model, i.e. the hierarchy levels and product lifecycle, serves as a basis for the \( \beta \)-version.

First, the reason to use a maturity model as an extension for the \( \beta \)-version is discussed. Thereafter, the two main design tools, the maturity model and the modernized Truijens Framework, are elaborated upon. Lastly, this chapter shows the design of the operational framework.

5.1 Operationalizing the framework

There are multiple approaches that can be used to extend the \( \alpha \)-version of the framework and create an operational tool. However, from a relevance perspective, extending the framework by maturity stages, is considered to be most beneficial. Based on expert interviews it was concluded that there is a need within businesses for development plans and roadmaps. Companies are eager to see a variety of stages and activities that help them to visualize and proceed with their smart manufacturing journey. This desire can be seen all over the world as technology roadmaps on both industrial and national level have been designed to support the fourth industrial revolution (Santos et al., 2017).

According to Weber, Königsberger, Kassner and Mitschang (2017), the fourth industrial revolution is mainly data-driven. Enterprises that want to take advantage of this revolution need to change their IT infrastructure. To make this change happen companies must be able to assess their current IT landscape and define a target architecture. Based on already existing reference architectures, like the ones presented in Section 3.1, features can be extracted and divided into levels to create a maturity model. The extraction of elements is already executed in the previous chapter. Now, these features can be categorized to form the various maturity stages.

5.2 Maturity Models

The reason to operationalize the framework by extending the framework with a maturity model is described above. There are a number of maturity models that can be used to create the Smart Manufacturing Framework. In this section, the various types of maturity approaches are discussed. Afterward, an insight is given in the already existing maturity models within the fourth industrial revolution. The maturity models are analyzed based on their fit with the purpose of this research and useful elements are extracted.

Maturity is the process of developing from an initial state towards a final state (Fraser, Moultrie & Gregory, 2002). This definition introduces the important concept of maturity stages. These stages have to be overcome before the end state is reached and are sequential and hierarchical (De Carolis, Macchi,
Kulvatunyou, Brundage & Terzi, 2017). Fraser et al. (2002) defined three types of maturity models here arranged in complexity, (1) Likert-like questionnaires, (2) maturity grids, and (3) CMM-like models, that all contain maturity stages. The CMM-like models are the most structured and provide clear guidance throughout the maturity levels, which is especially important when creating a roadmap. Therefore, the CMM structure serves as a guideline for designing the maturity model.

A literature review provided a list of 10 maturity models that are related to the fourth industrial revolution. The list can be found in Appendix F. The aim of the list is not to show completeness, but rather aim for a good representation of the variety in maturity models. The number of stages in the maturity models are either 3, 5 or 6. The focus of the maturity models ranges from smart factories to enterprises and also distinguishes between large enterprises and a Small and Medium-sized Enterprises (SME). It can also be noticed that a limited number of insights are given on specific activities, system implementation or IT infrastructure in any of the maturity models. Especially the maturity models that consider multiple organizational dimensions and focus on a broader scope have a very high-level approach showing little concrete content.

One of the maturity models uses an approach that is rather similar to the purpose of the Smart Manufacturing Framework. The System Integration Maturity Model Industry 4.0 (SIMMI 4.0) focuses on the software landscape of a company, which aligns with the information systems architecture approach for the design of the SMF. Furthermore, the framework uses the four key aspects of smart manufacturing, horizontal integration, vertical integration, end-to-end integration and technological support as the four main dimensions on which maturity can be reached (Leyh, Bley, Schäffer & Forstenhäusler, 2016). The dimensions and software focus correspond well to the scope that was determined in Section 4.2. Based on the analysis of the maturity models it is decided that the stages and dimensions of SIMMI 4.0 serve as a basis for the design of the β-version. A further elaboration on the SIMMI 4.0 maturity model is provided in the next section.

5.2.1 SIMMI 4.0

As was mentioned in Section 5.1 companies need to assess their current IT landscape to change their IT infrastructure according to smart manufacturing needs. SIMMI 4.0 is a tool that can be used to classify the IT system landscape against these needs (Leyh, Bley, Schäffer & Forstenhäusler, 2016). The model consists of the four key aspects of smart manufacturing that were determined in Section 4.2. Furthermore, the model consists of five maturity stages. The number of stages is justified by the fact that the smart factory is completed in the middle stage. The smart factory is one of the core concepts of smart manufacturing and an important milestone within the maturity stages (Yao et al., 2017). According to the SIMMI approach, a company does not need to reach full maturity for all the dimensions. Depending on their business goals one dimension can be more important than another. The various maturity stages can be summarized as follows:

1. **Basic Digitization** None of the requirements are met, the company is still orienting. Processes are not digitized and information is siloed.

2. **Cross-departmental digitization** Digitization has been implemented across departments and can partially be exchanged automatically. The company no longer exists of data islands. Enterprise systems are supporting both production and product development. Data exchange is not yet automatized, so previous and following process steps are not optimized.

3. **Vertical and Horizontal digitization** Industry 4.0 requirements are implemented enterprise-wide and services are available throughout the company by cloud solutions.

4. **Full digitization** Company is integrated into a value network, integration is enterprise-wide, cross-corporate horizontal and vertical. Information is automatically passed through the product lifecycle.

5. **Optimized Full digitization** All industry 4.0 activities within the company and across company borders are optimized. New business models are created based on the collaborations in the value network.
An additional benefit from the SIMMI model is that the model is validated by case studies. Based on a self-assessment the results showed that the maturity stages that were defined in the model, matched with the real-life situation of companies (Leyh, Bley, Schäffer & Bay, 2017). The activities that are defined to reach the next maturity stage are relatively abstract and it is hard to create a concrete roadmap based on the model. Furthermore, the maturity model does not include any visualizations or suggestions which enterprise systems should be integrated. Including these aspects would make the tool more pragmatic.

5.3 Modernized Truijens Framework

In Section 4.3 three dimensions for the architecture design were defined: the abstract, aggregation and realization dimension. These are all explicit dimensions shown in the 3D design cube (Grefen, 2016b). An additional and implicit dimension of the design cube is the aspect dimension. The aspect dimension defines the way someone looks at the architecture, it provides various viewpoints. It also determines which characteristics are included in the architecture. This dimension becomes important during the operationalizing of the framework because each maturity stage is a self-contained model that can consist of multiple aspects. To determine the aspects that are relevant for the SMF, the modernized version of Truijens Framework is used (Grefen, 2016b). The Truijens Framework defines 5 different views within the aspect dimension; 1) the data aspect describes the organization of data within information systems, 2) the process aspect describes the organization of processes in an information systems, 3) the software aspect describes the software modules and its connections, 4) the platform aspects describes underlying software and hardware in terms of computing and network facilities, finally 5) the organization aspect describes how the information system is embedded into an organization (Grefen, 2016b).

Due to a limited amount of time, it is not feasible to describe each of the aspects of the Truijens Framework. Therefore, three aspects that were considered most valuable and distinctive are chosen. Each maturity stage is described by the following three aspects, the process aspect, to provide a high-level overview of activities, the software aspect, to describe the information systems that are necessary, and lastly the platform aspect, that shows the integration between the modules. According to Li et al. (2018), the integration of information technology, industrial technology, and management technology is the core consideration for manufacturing enterprise. For that reason, the software aspects and platform aspects are chosen. The software aspect is a way to display the mentioned technologies, while the platform can visualize the integration. The process aspect helps to provide a high-level understanding of the business functionalities. The data aspect is also considered relevant to the smart manufacturing paradigm. However, describing all the data types, content, and flows would be too time-consuming. Additionally, the organization aspect is also not included in the framework. Similar to the data aspect, the organization aspect is also an important element for an enterprise to succeed in their smart manufacturing journey. Nevertheless, the organization aspect is very depending on a specific situation and already existing organization structure. Both the data and organization aspect are out of scope.

![Figure 5.1: Modernized version Truijens Framework (Grefen, 2016b)](image-url)
5.4 The Operational Smart Manufacturing Framework

In this section, the design of the operational Smart Manufacturing Framework is discussed. First, the result of the overall design is presented. Thereafter, an elaborate example is given for one of the maturity stages. Lastly, a summary for each of the stages is presented and some of the elements are discussed in more detail.

The Smart Manufacturing Framework consists of four dimensions. The $\alpha$-model designed in Chapter 4 is used as the basis for the development of the $\beta$-model. Therefore, the hierarchy dimension and the lifecycle dimension are directly plotted on the SMF. This basis is extended by the maturity dimension, defined by Leyh, Bley, Schäffer and Forstenhäuser (2016) and the selected aspects of the Truijens framework. When combining these dimensions a four-dimensional framework is created, the visualization is shown in Figure 5.2.

![Figure 5.2: Combining the four framework dimensions](image)

It is not easy for the human brain to understand a four-dimensional space, nor does it look visually appealing. For this reason, a similar approach is taken to the one of the 3D Design cube of Grefen (2016b). The four-dimensional space is reduced to a three-dimensional space. The hierarchy, lifecycle and maturity dimensions stay explicit, making the aspect dimension implicit. The implicit aspect dimension is not a visual part of the framework but stays hidden. This results in the reference model shown in Figure 5.3. The hierarchy levels are plotted on the vertical axis and display the exact same levels as in the $\alpha$-model. The product lifecycle as presented in Section 4.3.2 is positioned on the left horizontal axis. The right horizontal axis shows the extension for the operational model and displays the descriptors of the maturity stages. These descriptors are the same as the ones used in the SIMMI 4.0 maturity model. The intention is to stay as close to the stage description of SIMMI 4.0 as possible, as this framework is already assessed and validated. However, while designing the second maturity stage and discussing it with intended end-users and experts in the field, it was decided to adapt stage two.

The SIMMI 4.0 maturity model describes the second stage as digitization across departments, cross-departmental digitization. However, the description mentions that information can only be exchanged automatically among different departments and business areas. Based on discussions with experts it was decided this is not a likely situation, comparing it to actual cases. Companies first ensure that their own department is digitized and later have integrated systems across departments. Therefore, maturity stage two is defined as follows, departments are fully digitized and there are no data islands within departments anymore. Data sharing across departments is done actively but not yet automated, it is still based on requests. Another change that is made in the necessity of cloud-based solutions in maturity stage 3 and stage 4. The main point here is that the various systems should be integrated and accessible throughout the enterprise and beyond. This means that there should at least be middleware that integrates the information systems, but it is less important where it is integrated. This can occur in the cloud, which improves standardization purposes, but can also be in a locally controlled data center. For this reason, the cloud is merely a possibility to position the system, but the middleware is a necessity to enable the functionality. Lastly, SIMMI 4.0 suggests that product design and development are not digitized in stage 1. Again experts say that this is not the real-life situation, because almost every company designs using digital tools. Therefore low-level product design is digitized for stage 1. A description of the SIMMI 4.0 maturity stages is given below.
1. **Basic Digitization** The company does not have any smart manufacturing capabilities. Processes are only partially digitized and information is scattered throughout the organization. Tools for digital product design are available.

2. **Cross-departmental digitization** Information is no longer siloed but can be accessed within the departments. Enterprise systems are supporting both production and product development. Data exchange is not yet automatized.

3. **Vertical and Horizontal digitization** Industry 4.0 requirements are implemented enterprise-wide. Production and product development systems are integrated and information is exchanged automatically. The company established the Service-Oriented principles. Services can be made available throughout the company by cloud solutions.

4. **Full digitization** Company is integrated into a value network, integration is enterprise-wide, cross-corporate horizontal and vertical. Information is automatically passed through the product lifecycle and across the value chain.

5. **Optimized Full digitization** All industry 4.0 activities within the company and across company borders are optimized. New business models are created based on the collaborations in the value network.

As the framework is now a 3D cube it is possible to rotate it to change the positioning of the dimensions, for example, swap the maturity and hierarchy dimension. It is also possible to make one of the current explicit dimensions implicit and therefore make the aspect dimension explicit. For the remainder of the report, the visualization as is presented in Figure 5.3 is used. This decision is made because it maps directly to the maturity models shown in Figure 5.4. The Smart Manufacturing Framework is the main artifact of this research and contains itself, several models. These models form the reference architecture. By cutting the reference model in vertical slices reveals the reference architecture, showing the individual maturity stages and the positioned elements. The hierarchy level is positioned on the left side of the model, similarly to the SMF, and the product lifecycle is positioned on top. The maturity stage is shown on the right side of the model, also in line with the SMF. The until now explicit aspect dimensions are now revealed in separate models. Each maturity stage is designed using three aspects of Truijens framework (Grefen, 2016b). This design leads to a model that shows the three aspects and an integrated model of the software and platform aspect. This combination provides an insight into the system integration. An example of a complete maturity stage, showing the four models, is given in Figure 5.4. In the remainder of the document, the visualizations of the aspects will be referred to as maturity models.

According to Fraser et al. (2002) a maturity model should preferably present six components, (1) stages, (2) stage descriptors, (3) summary of the stage, (4) a number of dimensions, (5) a number of elements in the dimensions, (6) and an activity description for each stage. The five stages and descriptors are already shown in Figure 5.3. The number of stages, as well as the stage descriptors, are kept exactly the same as in the SIMMI 4.0 model as a basis for the reference model. The descriptive summaries are adapted and provided earlier in this section.
The number of dimensions, which are in this case the aspects, and an example of elements within the dimension are shown in the figure above, Figure 5.4. The elements are adapted for each aspect, such that they represent an accurate viewpoint. This means overall functionalities in the process aspect, that are specified using information systems in the software aspect and middleware is used in the platform aspect. All these elements have to be positioned according to their hierarchy level, lifecycle phase, and maturity stage. This model contains 5 hierarchy levels, 3 lifecycle phases, 5 maturity stages and 3 aspect dimensions, which leads to $5 \times 3 \times 5 \times 3 = 225$ cells. This means that there are at least 225 design decisions made during the design of this reference model, as each cell can contain either 0, 1 or n elements. It is difficult to provide a tight argumentation for each of these design decisions. In some cases the positioning of elements can be argued using literature, for example when they are included in a standard. Nevertheless, it can be the case that literature does not provide a single answer or that some of the elements are not yet discussed in research. Then positioning is based on expert knowledge or an own interpretation from existing use-cases. To ensure the readability of the report, only the design approach of stage 1 is elaborated upon in the next paragraph. The remainder of the stages is summarized in Table 5.1. In case you, as a reader, are interested in the decisions that are made for each maturity model, the visualizations of these models can be found in Appendix G, together with the design choices that are written down in bullet points.
5.4.1 Elaboration Maturity Level 1

Maturity Level 1 is described as basic digitization, with no smart manufacturing capabilities available. Only limited digital support for development processes is implemented. The company consists of data islands and there is no or limited digital interaction between the departments. In case enterprise systems are available they only support functionalities within their own department. Data integrity is not ensured.

**Process Aspect**

The process aspect shows the overall functionalities that are available within the organization and can involve multiple hierarchy levels or lifecycle phases. Due to the limited support for product information is scattered across the organization (Batenburg, Helms & Versendaal, 2006). For the development phase, this means that information on mechanical components is stored separately from information on electrical components and integration only happens when the different designers decide that components must be combined. The functionality *decentralized product data management* is positioned on the production line level, as the components should integrate on this level, but are still siloed. According to Leyh, Bley, Schäffer and Forstenhäuser (2016), there is no digital support for product development, which suggests that software tools for design are absent. However, based on expert knowledge this is an assumption that does not match with reality in industries. For this reason, the process of product design is supported digitally. Hence, the functionality *siloed digital product design* is positioned on a work cell level where the design of components takes place. The positioning is based on the defined relations between the hierarchy levels and lifecycle phases presented in Figure 4.11.

It is assumed that at stage 1 enterprises possess machines and robots that execute manufacturing activities. The manufacturing equipment available on the shop floor contains standard machine software. This enables *partially digitized production management* for a production line and *single machine control* on a lower level. The functionalities of the well-known manufacturing pyramid are used to describe the site level. Production is planned on a site level and business resources are planned on enterprise level (American National Standard, 2005). Based on the ISA-95 standard for manufacturing operations can be defined, *production operations, quality operations, maintenance operations and inventory operations* (American National Standard, 2005). These are activities for production planning and are thus positioned on a site level. The functionality for *resource management*, which is more a business functionality, is positioned on a site level. As the company still consists of data islands these functionalities all exist individually. This means that a certain group is responsible for inventory operations and another group is working on production operations. All schedules and plans that these functionalities require are shared on paper with shop floor workers, such that the processes can be executed. Note that there is no integration between the various areas within the company.

In maturity level 1 the company is considering mainly its own operations and does not look for cooperation with customers. This is shown by the fact that the company is still focusing on goods and is not service-oriented yet (Leyh, Schäffer, Bley & Forstenhäuser, 2016). The relation with the customer is mainly focused on selling the product, so limited data and information are gathered. For that reason, the functionality for support towards the customer is *ad-hoc production support* and only happens when the customer requests it.

**Software Aspect**

According to the functionalities the product development is already digitally supported. Therefore, software tools are available for the design of products. A product is not simply designed using a single tool. It exists of different components that all have different specifications and thus requires a specific software tool. These tools are often split into three different categories: Computer-Aided Design for mechanical components(M-CAD), E-CAD is used for electrical components and for the software part a Software Development System (SWD) is used. This distinction and placement are verified with expert knowledge within Atos and the CAD system is also visualized in the Smart Manufacturing Ecosystem (Lu, Frechette & Morris, 2016). The design tools are positioned on a work cell level as they focus on component design. The component data is managed on a production line level in databases. As information is still siloed within the departments, each system is linked to its own database. A developer can save its design progress in a database and work further in the morning, but information on requirements for compatible parts is unavailable.

On the work cell level machines are equipped with a Programmable Logic Controller (PLC). A PLC is a remote terminal unit, that due to the programming capabilities has established a more sophisticated
manner of monitoring and control (Endi, Elhalwagy et al., 2010). Equipping machines with a PLC is a common practice in current industrial systems and provides real-time operations, based on its connection with sensors and actuators and the higher level SCADA system (Tomleijn & Grønbæk, 2017). A SCADA system, which stands for Supervisory Control and Data Acquisision is, similarly to the PLC, widely used for industrial processes. The SCADA system is solely a software system, that interfaces with hardware via a PLC (Daneels & Salter, 1999). According to the ISA-95 manufacturing pyramid supervising and control is a level 2 functionality, which indicates that it should be placed on the level of a production line. One of the main functionalities of SCADA is logging, which can be thought of as a medium-term data storing. This data can be used by information systems on a higher level, that are responsible for the site level functionalities. In this stage data is still siloed so for each of the functionalities at a site level, there is an individual information system that executes it. The Manufacturing Execution System takes care of the actual scheduling of operations, the warehouse management system (WHMS) keeps track of the inventory levels of the various components and products, production quality is ensured by the Quality Management System (QMS) and lastly maintenance of machines is scheduled and kept track of using the Maintenance Management System (MMS). According to Erasmus et al. (2018), these systems are all level 3 functionalities and thus are placed on top of the SCADA system. The resource planning of the entire enterprise is executed by an Enterprise Resource Planning system and is therefore placed on an enterprise level. All these elements together form the manufacturing pyramid (Lu, Frechette & Morris, 2016).

There is not much digital support for when the product is in use and to provide services. Customer data is kept in an excel file and no proper Customer Database (CDB) is established yet.

**Platform Aspect**

Not many platforms are needed within the first maturity stage. Systems and information are still scattered across the company and interoperability between systems is rare. In the development phase, each design system stores the files in a siloed database. This means that there is one-to-one module coupling between the systems, so the interoperability pattern between the systems is direct invocation (Grefen, 2016b). A Fieldbus enables the connection between SCADA and PLC. A field bus is an umbrella term for standards such as MODBUS and TCP/IP (Endi, Elhalwagy et al., 2010). This connection can be either hardwired, point to point, or via radio.
5.4.2 Summary of Maturity Stages

Table 5.1 includes a summary of the elements that are relevant for each maturity stage. The table can be seen as a delta matrix as only the elements that changed or are new are considered in the next stage, in other words an incremental description is provided. This provides an overview of which activities or implementations are necessary to reach the new maturity stage. The columns represent the three aspects as for each of the aspect different activities might be necessary to reach the next stage. The same holds for the various lifecycle phases, once the focus of a company lays with one of the phases it is possible to only focus on the elements that are important for that phase. Lastly, a short summary is given for each of the stages as a whole.

<table>
<thead>
<tr>
<th>Maturity Stage</th>
<th>Process Aspect</th>
<th>Software Aspect</th>
<th>Platform Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic Digitization</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>Siloed Digital Product Development</td>
<td>Product Design support, E-CAD,M-CAD,SWD</td>
</tr>
<tr>
<td></td>
<td>Production</td>
<td>Decentral Production Management</td>
<td>Machines are connected by PLC and controlled by SCADA. Operations Management systems are siloed, MES, QMS, WHMS, MMS, and partially available. ERP system on Enterprise Level</td>
</tr>
<tr>
<td></td>
<td>Usage/Service</td>
<td>Ad-Hoc Services</td>
<td>Excel as customer database (CDB)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Cross-Departmental Digitization</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development</td>
<td>Product data management</td>
<td>Digital PDM support, all design elements from the work cell are now stored in systems engineering software. On a higher level, information is stored in a PDM and PLM</td>
</tr>
<tr>
<td></td>
<td>Production</td>
<td>Coordinated Production Support</td>
<td>Some machines are equipped with IoT software and sensors and actuators. Integrated Manufacturing Operations Management System (MOMS) and orchestrated manufacturing operations, using a business process management system (BPMS)</td>
</tr>
<tr>
<td></td>
<td>Usage/Service</td>
<td>Decentralized support</td>
<td>Customer Database System (CDB)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>
The smart factory is established, the full manufacturing pyramid operates autonomously. Enterprise-wide digitization of product development, production, and services. Enterprise Service Bus and Cloud services are established to connect the various enterprise systems and serve the entire company.

<table>
<thead>
<tr>
<th>Horizontal and Vertical Digitization</th>
<th>Development</th>
<th>Digital Product Twin</th>
<th>Service Lifecycle Management (SLM) available to build a service-oriented organization and manage the services that are available.</th>
<th>Enterprise Service Bus to integrate support product data management systems. The ESB is also used to integrate PLM, SLM, and ERP on an enterprise level to support both development and production. These systems can be in the cloud, private or public, but are always integrated by an enterprise bus.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Smart Factory</td>
<td>PLM and SLM also integrated on an enterprise level within the production phase</td>
<td>IoT Communication Layer to process real-time data between work cell and site level, combined with a Smart Factory Information Service Bus (SIBUS). SIBUS integrates both information systems with shopfloor hardware and IoT components. The ESB is also used to integrate PLM, SLM, and ERP on an enterprise level to support both development and production. These systems can be in the cloud, private or public, but are always integrated by an enterprise bus.</td>
<td></td>
</tr>
<tr>
<td>Usage/Service</td>
<td>Decentralized Customer Support</td>
<td>CDB</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Companies digitization stretches beyond corporate borders. The role of the customer and the fast innovation cycle becomes important for improved development and autonomous production. Next to the product and production twin, there is also a customer twin. Information in enterprise systems is standardized and accessible throughout the lifecycle, using cloud services. Suppliers and customers are all integrated into a collaborative value network.

<table>
<thead>
<tr>
<th>Development</th>
<th>Integrated Product Lifecycle support</th>
<th>PLM and SLM transfer to the network level to ensure that development activities are accessible in the value network.</th>
<th>Both information systems on a network level can be in the cloud and are connected via an ESB. The cloud helps to standardize, such that data can be used across the supply chain.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Optimized Smart Factory</td>
<td>Supply Chain Management (SCM) is added to support the production based on information from suppliers and customers, which helps to realize the optimized smart factory. For production PLM and SLM are on a network level to enhance the collaborative value network.</td>
<td>The information systems on a network and site level can be in the cloud, especially on network level this is a good solution for standardization. An ESB serves as middleware to integrate the information systems on network and site level.</td>
</tr>
<tr>
<td>Usage/Service</td>
<td>Integrated Service Lifecycle Management</td>
<td>IoT Software embedded in the product in use. CRM system that keeps track of the customer information. The SLM and PLM stretch towards the Usage/Service to provide services to the customer and keep track of exact product data.</td>
<td>The IoT communication layer also stretches towards this phase to ensure real-time data from the product in use is captured. The CRM is connected to the other enterprise systems by an ESB, in the cloud or local data center.</td>
</tr>
<tr>
<td>Development</td>
<td>Optimized Digital Twin and Product Lifecycle</td>
<td>Improved use of available data from the enterprise systems. Using data analytics and simulations to respond quickly to changing customer demands.</td>
<td>All enterprise systems are in the cloud to ensure security, availability and the standardization of data. Interoperability is ensured by the ESB.</td>
</tr>
<tr>
<td>Production</td>
<td>Optimized Smart Factory and Smart Enterprise</td>
<td>Real-time analysis based on shop-floor data and data from the collaborative value network. Customer orders can be produced autonomously, using flexible manufacturing systems.</td>
<td>All Enterprise systems are in the cloud to ensure security, availability and the standardization of data. Interoperability is ensured by the ESB.</td>
</tr>
<tr>
<td>Usage/Service</td>
<td>Connected Customer</td>
<td>Data from the product in use is processed and used to optimize the development and production phase. Sales configurator is accessible for the customer and generates orders that are fulfilled automatically using the production systems and supply chain. Predictive maintenance is an integrated service for the client.</td>
<td>The connectivity of the real-time product data plays an important role to optimize the entire enterprise.</td>
</tr>
</tbody>
</table>
CHAPTER 5. OPERATIONAL FRAMEWORK DESIGN

The table above can be used to determine which activities should be performed to reach the next stage, as it provides an overview of the deviations between the sequential stages. While discussing the framework with experts at Atos and also based on the results of the implementation, some of these deviations were considered to be a bigger game changers than others. Therefore, a couple of these activities are highlighted to emphasize their importance.

To reach maturity stage 2 it is important that both the product development and production are coordinated. For product development, the implementation of a PLM system is key. According to Batenburg et al. (2006), implementation of a PLM system is at first a data management problem that is dealt with on a departmental level. This matches with the adapted description of maturity stage 2. The activities still happen on a departmental level and not yet across departments. Furthermore, it is also commercially more attractive to split the activities of product development and production engineering on level 2 and integrate these processes on level 3, as this often resembles the real world scenario. For the coordinated production support, the implementation of the Manufacturing Operations Management System is important. Often a company mainly considers a Manufacturing Execution System that in its broad definition suggests it contains all the functionalities of a MOMS (i.e. production, inventory, maintenance, and quality operations) (Erasmus et al., 2018). A visualization including the MOMS is chosen to explicitly show the integration of those functionalities into one operating system for production is an important milestone and highlights an aspect that is not always considered.

The previous paragraph also indicates an important and valuable change to reach level 3, namely the integration of the functionalities product development and product engineering. The ISA-95 standard mainly suggests vertical collaboration from the Enterprise Resource Planning system to production. The ERP system takes care of production planning and scheduling, whereas product-related data for production management are recorded in the MES (Khedher, Henry & Bouras, 2011). However, with the evolved PLM systems the same information can be stored in multiple systems. Therefore, the ERP system does not have to serve as an interaction between PLM and MES, but it is better to have a direct connection between the three systems. This way detailed product data and even detailed work instructions can be sent directly from the PLM to the MES and only higher level production scheduling is executed by the ERP system, Figure 5.5. The data exchange between these platforms also requires the implementation of a platform to ensure the interoperability of these systems. As the enterprise is also becoming service-oriented the Enterprise Service Bus is a logical solution. This common middleware allows for flexible m-to-n module coupling (Grefen, 2016b). To support the decision for ESB within the fourth industrial revolution an example of an I4.0 application is used. In this example of an Industry 4.0 application, the enterprise service bus is used as middleware between the ERP system and a database for static data, as well as a lower level SCADA element (Marseu, Kolberg & Weyer, 2017).

![Figure 5.5: Integration PLM, MES and ERP](image)

Figure 5.5: Integration PLM, MES and ERP, adapted from Khedher, Henry and Bouras (2011)
The last activity that also leads to an important change within and beyond the enterprise is the establishment of a collaborative value network at maturity stage 4. Using the Internet of Things to gather information from the product in use and thereby connecting the customer is an important step for improving the product lifecycle. A closed-loop lifecycle ensures that within each lifecycle phase the relevant data is available (Kiritsis, 2011). For example, the designers know exactly which components caused troubles during production, based on the shop floor information. Maintenance experts know, based on predictive maintenance analysis, when service must be provided and are assisted during their work using Augmented Reality. The connection of the customer and the supplier leads to a fast innovation cycle based on accurate data, such that a quick and flexible response to the changing environment is possible. Figure 5.6 shows how the data from the physical world is used to create three digital twins in the virtual world, the connection between OT and IT. The digital twin is a virtual model of a complex product and allows for probabilistic simulations to mirror the life of its physical twin (Tao et al., 2018). It consists of a physical and virtual component and data connecting those two. The virtual model can be used for data analytics to improve the lifecycle, but can also help to deploy augmented and virtual reality.

![Figure 5.6: Closed Product Lifecycle, taken from Atos documents](image)

The Smart Manufacturing Framework, as it is visualized in Figure 5.3 can be used as a tool to support companies in the development of smart manufacturing practices. The individual maturity stages show a roadmap from a very early stage of implementation until an optimized collaborative smart manufacturing network. The functionalities and elements displayed in the models help to create an idea of the necessities to engage in smart manufacturing practices. The framework does not claim to be complete but does show some of the key elements for the development of smart manufacturing. How the framework can be put into use is presented in the next chapter.
Chapter 6

Framework Implementation

The implementation of the artifact is the fourth step in the problem-solving cycle of van Aken et al. (2012) and is used to measure the relevance of the framework. The implementation of the framework takes place in two real-world scenarios, in other words, a case study is conducted at two different companies. The β-version, the smart manufacturing framework is implemented, as it was concluded that the α-version of the framework was not suitable for implementation. First, the implementation approach is discussed. Second, the meta-results of the implementation are presented. Lastly, a short conclusion is provided on the overall results of the implementation.

6.1 Implementation Approach

The implementation of the framework is divided into four main steps, as shown in Figure 6.1. First, the current maturity stage is assessed, to create a proper starting point. Second, the desired maturity stage is determined, such that a road between the two can be built. However, before that road can be created, the differences between the two stages must be analyzed. Lastly, the activities that are necessary to reach the desired maturity level are selected and described. This provides the final result of the implementation, the smart manufacturing roadmap. Creating the roadmap for the participant is not the only goal of the case study. A second goal is to validate the usability of the framework when it is applied in industry. Additionally, it is verified if the maturity stages and the defining elements are chosen correctly. Therefore, multiple methods are used in the first and second step of the implementation to determine if these methods provide a similar outcome. The usage of the various methods is based on the assessment of the SIMMI 4.0 maturity model, where they conducted a self-assessment based on a high-level overview as well as a more detailed questionnaire (Leyh et al., 2017). The implementation steps and different methods are described in this section.

Step 1: Assess current maturity level

The goal of the first step is to determine the current maturity level of the enterprise that serves as a starting point for the transformation. For the purpose of validation, three different approaches are used. The first approach is a high-level assessment, only based on the main functionalities of each maturity stage. The second approach is a detailed questionnaire, based on the practices within the four key smart manufacturing aspects. Lastly, the current situation of the organization is compared with the four maturity models of the maturity stage that resulted from the questionnaire.
**High-level Assessment based on Maturity Model**

The high-level assessment is based on an overall description of each lifecycle phase per maturity stage. This description can be seen as a summary of Table 5.1, where the aspect dimensions are no longer split. The table is already too detailed for an interviewee to easily determine the current maturity stage. Therefore, the high-level overview of the maturity models is visualized and shown in Figure 6.2, to create a first insight into the companies maturity level. The descriptions in the maturity table are based on functional elements from the actual maturity models.

The interviewee is asked to position the company, for each of the life-cycle phases. When the interviewee is in doubt between two stages, it is decided to take the lower maturity stage. It is often the case that some activities in the higher maturity stage are already executed, but full establishment is not yet reached. Therefore, the stage that is fully established is marked as the current situation. The positioning of the current IT landscape based on the lifecycle phase can lead to different maturity stages. For example, in the development phase the company can already establish a digital product twin, but at the same time provide ad-hoc services. This results in a scattered IT landscape based on the maturity table and identifies a gap within the current state.

![Figure 6.2: Maturity table for the life-cycle phases](image)

**Detailed questionnaire**

The second method is a detailed questionnaire based on the four aspects of smart manufacturing: (1) Vertical Integration, (2) Horizontal Integration, (3) End-to-End Integration, (4) Technological support. The questionnaire is used in a face-to-face interview. There are three perspectives on an interview method: (1) Neopositivism, the interview is used as a tool to collect data, (2) Romanticism, the interview is a human encounter to reveal experiences, (3) Localism, puts interviews into a social context and studies an empirical situation (Qu & Dumay, 2011). In this situation, the interview is used to transfer data and knowledge objectively. The interviewee tends to tell the truth about their current situation and their IT landscape. A Neopositivism perspective suggests the use of either a structured or semi-structured interview. In a structured interview, the interviewer asks a set of questions that are pre-established and the interviewee can only answer based on a limited number of response categories. Strictly, it does not allow for any deviations from the script. A semi-structured interview also uses a pre-established set of questions but these questions less strict and narrow. The questions are divided into themes and use probes to stimulate more elaborate responses. This approach is mainly based on guiding the interview to stay on the topic as planned.

The approach that is used for the implementation is semi-structured. The aim is to receive elaborated responses because only a limited amount of interviews can be conducted. The questions serve as a guideline to discuss the four key aspects of smart manufacturing as well as the relevance for each lifecycle phase. The semi-structured approach leaves some flexibility during the interview, to ignore questions that are irrelevant and ask follow-up questions where necessary. For example, when a company only executes the final assembly of a product, the automation of the factory might be irrelevant. In that case, questions related to IoT on the shop floor and system integration in the production phase can be
The questions are based on the questionnaire used for the assessment of the SIMMI 4.0 maturity model of Leyh et al. (2017) and the questionnaire for the maturity and readiness model for industry 4.0 strategy of Akdil, Ustundag and Cevikcan (2018). The questionnaires are considered to be a valid basis as both maturity models were assessed using these questionnaires. The complete questionnaire consists of 30 questions and sub-questions and can be found in Appendix H. Based on the answers the current maturity stage of the company can be determined. The example questionnaires use a point system to determine the maturity stage. Their approach leans towards a structured interview and many of the questions have a limited number of possible answers. For each of these answers, a number of points can be scored. The rounded down average that results from the questionnaire, is the maturity stage that is determined. As the approach for this interview is semi-structured, it is difficult to use a point system. Due to the fact that there are no given answer possibilities, it is hard to give a point to a certain answer. The open answers are used to determine which functionalities, systems and platforms are in place in the current IT landscape. These can be mapped to the same elements in the maturity models belonging to a maturity stage. In case all elements or almost all elements are in place for a certain stage, the current maturity stage is determined.

Model-based verification

The outcome of the questionnaire and high-level assessment is compared with the maturity models. Both the integrated aspect, including the software and platform aspect, and the process aspect are used to verify the results. The interview is asked if the models do represent the current processes and IT landscape that is present in the company. In some situations, it might be the case that certain elements that are displayed in the models are missing in the current IT landscape of the company. This means that there exists a gap in the current maturity level that should be addressed.

Step 2 Determine Industry 4.0 vision

The goal of the second step is to determine the desired state of the organization, based on the maturity stages of smart manufacturing. Again multiple approaches are used to determine the TO-BE situation as was used in the AS-IS situation.

High-level desired maturity stage based on maturity model

Similar to the approach for the current situation, the maturity model, Figure 6.2, is used to create a first insight into the desired maturity level. This provides again the possibility to position the company at different maturity stages based on the various life-cycle steps.

Ranking of smart manufacturing key capabilities

The second method provides more insight into the goals of the company regarding the fourth industrial revolution. Based on the four key capabilities of smart manufacturing as determined by Lu, Frechette and Morris (2016), it is possible to determine what is most relevant to a company. The key capabilities are (1) Productivity, high throughput and reduced labor hours, (2) Agility, quickly respond to changing demands, (3) Quality, customer service, innovativeness and quality of the product, (4) Sustainability, product durability and recyclability. Each of these capabilities corresponds to aspects of the smart manufacturing ecosystem, such as Supply Chain Management and Design for Manufacturing and Assembly. An overview of the aspects and the corresponding capabilities is provided in Table H.1, which can be found in Appendix H. Based on the table introduced by Lu, Frechette and Morris (2016), a mapping to the functionalities that are represented in the SMF is made, shown in Table 6.1. The table works as follows. Once productivity is ranked as capability number one it is verified by asking questions related to the functionalities corresponding to productivity. An example question can be "is a bi-directional automated flow in the manufacturing pyramid necessary?". This corresponds to a level 3 maturity, the establishment of a smart factory.
Table 6.1: Smart manufacturing capabilities linked to maturity model stages

<table>
<thead>
<tr>
<th>Productivity</th>
<th>Agility</th>
<th>Quality</th>
<th>Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Design for Manufacturing</td>
<td>3 Product Twin</td>
<td>2 Manufacturing Pyramid</td>
<td>2 Manufacturing Pyramid</td>
</tr>
<tr>
<td>3 Smart Factory</td>
<td>4 Fast Innovation Cycle</td>
<td>3 Continuous Process Improvement</td>
<td>3 Smart Factory</td>
</tr>
<tr>
<td>4 Smart Connected Factories</td>
<td>4 Flexible Manufacturing System</td>
<td>4 Fast Innovation Cycle</td>
<td>4 Integrated PLM</td>
</tr>
<tr>
<td>5 Optimized Smart Factories</td>
<td>4 Integrated SCM</td>
<td>5 Mass Customization</td>
<td></td>
</tr>
</tbody>
</table>

**Model-based verification**

Once the desired maturity stage is established using the previous two methods, it is verified using the models presenting the process aspect and integrated aspect. Together with the interviewee the processes and the systems are compared with the expectations and the vision, to evaluate the necessity of the elements that are displayed in the models. It can happen that the interviewee concludes that some of the elements in the maturity model are not relevant, maybe they do not want to track the product in use. In that case, the elements that represent monitoring a product in use are left out of scope. It can also be the case that the maturity for those aspects should be positioned on a lower stage than the stage that was found using the previous two methods.

**Step 3 Gap Analysis**

In order to construct the roadmap, a gap analysis is performed between the two maturity stages. In case analysis must be made between stages 1 and 3 or 2 and 5, the intermediate stages are also considered. An example of a gap analysis of the platform aspect between maturity level 2 and 3 is shown in Figure 6.3. First, it must be noticed that the Enterprise Service Bus captures two lifecycle phases and is extended to the enterprise level. This ensures interoperability between the development and production phase as well as vertical integration of the systems. Furthermore, enterprise information systems can be in a cloud application. As the cloud is not an actual platform it is here visualized using an annotation, based on the example of Grefen, Vanderfeesten and Boultadakis (2016a). To establish the smart factory, the IoT communication layer is necessary to connect the information systems to the shop floor. Additionally, a dedicated smart factory BUS for connectivity between hardware and software, SIBUS, is implemented.

![Figure 6.3: Gap Analysis between maturity level 2 and 3](image)

Comparing the models provides information on the systems that must be installed, the need for platforms and the level of system integration. However, it also implies other activities that are not directly visible in the maturity models. An IoT communication layer implies that data from the shop floor is gathered.
and processed on a higher hierarchy level. This means sensors are necessary to collect the data, data models are necessary to run data analytics and it must be clear which data must be gathered. These elements are implicit in the models but do play an important role in the successful establishment of the maturity stages. The activities that are necessary to bridge the gap between the AS-IS situation and TO-BE situation, both implicit and explicit, are put into a logical order that forms a roadmap. The roadmap can be executed such that the desired maturity level is reached and full value can be extracted.

**Step 4 Create a Roadmap**

The roadmap is the result of the implementation of the Smart Manufacturing Framework. It includes activities and actions that must be taken to reach the desired maturity level. These actions can be derived from the various models and constructed into a sequence of steps. The employees at Atos that will use the framework can provide an in-depth roadmap that includes an overview of data mitigation and integration as well as software packages and functionalities of specific vendors. However, for this situation to give a first introduction to the application of the framework, the roadmap is constructed on a higher abstraction level. In the next section two summaries of roadmaps are given, to create a general feeling of the final result.

**6.2 Implementation Results**

As was mentioned in the introduction of this chapter, the above described approach is applied to two real-life scenarios. Both companies agreed with the fact that the results are used for this report and thus will be available for the public. However, the results are anonymized, such that none of the answers can be related to a specific company. The interview is not transcribed, but audio recordings of the interview have been made and are accessible upon request (Participant1, 2019; Participant2, 2019). Note that these audio recordings are also anonymized. A short description of both case-studies is given below.

The first company is a start-up in the automotive industry and falls in the range of 50-99 employees. As a startup, it has no restrictions due to legacy systems and is at the start of creating their IT landscape, a greenfield starting point. The company is focused on smart manufacturing and wants to apply these practices to their company. The interviewee is mainly involved in the development phase but also has the knowledge and vision for the other phases of the lifecycle. Furthermore, the interviewee is aware of the current IT landscape as he works within the IT department.

The second company is a well-established Original Equipment Manufacturer (OEM) in the food processing industry. As OEM the main production activities focus on the assembly of the sub-systems to create a final product and the production of small components to execute the assemblage. This international company has over 5000 employees and is far more advanced in establishing their vision for smart manufacturing practices. The interviewee mainly focuses on software development for the product in use and is therefore also at the development site. However, due to a great level of experience, the interviewee has a good insight into the current IT landscape.

First, the main results of each activity are discussed for case-study 1 and thereafter for case-study 2. The section is concluded by analyzing the main results and the implication of these results on the framework.

**6.2.1 Case-Study 1**

The overall outcome of the assessment of the current and desired maturity stage is provided in Figure 6.4. The blue cells show the current maturity stage and the green cell show the desired maturity stage. It can be seen that the current IT landscape is not positioned on a single stage. The production phase is still on a level 1 maturity, whereas the other lifecycle phases are already evolved to stage 2. The desired maturity stage is set on maturity level 4. The optimization of the entire ecosystem was at this moment not considered as the final situation, as the main goal is now the implementation of the right systems.
CHAPTER 6. FRAMEWORK IMPLEMENTATION

Figure 6.4: Main results Case 1

Step 1

First, the interviewee is asked to position the company based on the maturity table, the high-level assessment. The company manages its data using a PLM system, but it is still departmental. Therefore development is positioned on maturity stage 2. The company is not yet producing their product, which makes the placement of the production phase hard. A couple of test products were produced in a coordinated manner. The production phase is positioned at the very beginning of stage 2. Currently, the services that are offered are still decentralized. Customer data is kept, but this is mainly for sales purposes. Lastly, the organization of the company is departmental. This results in an overall high-level view of maturity stage 2, with a side note for production that this is positioned at the very beginning.

The results of the detailed questionnaire are quite similar. To support the vertical integration within development CAD tools, a PDM and a connection to a PLM are available. The ERP system is implemented for resource planning, which resources are needed at which time. However, there are no systems that support the production environment except for the ERP system, so no vertical integration for the production environment. There is no CRM system to support the connection with the customer, limited horizontal integration. The interoperability between PLM and ERP is offline. The suppliers are now managed in the ERP system, so no individual SCM system. For end-to-end integration, there is already a link between production and development, as the manufacturing processes are available in the PLM system. This is mainly due to a lack of a MOMS. Lastly, the PLM system is already a cloud-solution. However, it is only accessible within the enterprise. Using these outcomes results in almost the same maturity stages as the high-level assessment. All elements for maturity stage 2 are present, except for the elements in the production phase. Therefore, the production phase is positioned on maturity level 1 and the remaining phases are placed on level 2.

The maturity models were used to verify the elements depicted in these models. Based on the models for maturity stage 1 and 2, it was indeed possible to map the functionalities and software systems to the current situation. However, it was also concluded that the cells in the production phase on the two lowest level were not relevant for this company. Automation of machines is not applicable in this situation. The company uses a cloud solution for PLM, but the cloud is not included in the stage 2 maturity model. However, as the cloud is not a platform but merely an annotation it is decided that this is not a mistake in the model. Especially, because the PLM is not integrated with one of the other enterprise systems using an enterprise bus.

The evaluation of the AS-IS situation led to the following visualization, shown in Figure 6.5. The red circles show the focus areas that are still lacking for that maturity stage.
Step 2

During the questionnaire in step 1, there were already answers that helped to determine the desired situation. However, for the consistency of the implementation approach, these answers are not taken into account. It is important to know upfront that this company is restricted by many regulations that they have to comply with. For this reason, the desired maturity stage was very clear “we have to move to stage 4”.

Traceability of the product is extremely important from source to customer, therefore there should be integrated product lifecycle support. Although a Smart Factory with autonomous shop floor is not directly necessary, it is preferable to have orders automatically transformed into work instructions, such that the shop floor employees can assemble the product. Similarly to the integrated product lifecycle, the integrated service lifecycle management is necessary to support the product and provide customers with services. Furthermore, the value network must be established such that product information is available across the supply chain.

The smart manufacturing capabilities were ranked as follows: (1) Quality, (2) Agility, (3) Sustainability and (4) Productivity. Based on the quality aspect product lifecycle management should be across the entire lifecycle. In case something is wrong with the product immediate improvements must be made. This complies with the Fast Innovation Cycle, established on level 4, which comes together with the integrated product lifecycle if data is used properly. For agility, there are three functionalities that are linked to stage 4. The Fast Innovation Cycle was already determined, but also integrated SCM and routing of the production are considered to be relevant aspects. The integrated PLM must be met for sustainability, level 4. Productivity is not considered important and a smart factory on level 3 would be sufficient as was mentioned above. However, the integration with the network is considered relevant for the company and therefore the TO-BE state is positioned on maturity stage 4. The missing aspects are visualized in Figure 6.6. What is interesting is that the IoT software on the product in use was considered to be out of scope, while the fast innovation cycle is a desired functionality. This had to do with the fact that accurate information about the product on each component is desirable, but real-time performance is not. Hence, improvements and activities based on accurate product data is still a relevant functionality for this company.

Step 3 will not be discussed explicitly here, as the gaps are already represented in the visualizations of step 1 and step 2. Furthermore, the gaps are also addressed during the roadmap design. The gap analysis can be found in Appendix H.
Step 4

A summary of the roadmap just containing the main activities is provided here. A more elaborate version can be found in Appendix H. The roadmap is based on the results from step 1 and 2. First, the current IT landscape needs to be brought to one maturity stage, the production phase must move from stage 1, or maybe even stage 0, to 2. Thereafter, the whole IT landscape should move from stage 2 to 4, including some activities to establish stage 3. It might be the case that not all elements of stage 3 have to be implemented before the company can move to stage 4.

- **Activity 1** Implement a Manufacturing Operations Management System, this can be a MES system with additional functionalities.
- **Activity 2** Integrate the PLM and the MES system.
- **Activity 3** Implement the SLM system and establish a service-oriented organization.
- **Activity 4** Establish the digital product and production twin, by building simulation models and creating data analytics models.
- **Activity 5** Make the PLM system accessible to the suppliers.
- **Activity 6** Implement a SCM system.
- **Activity 7** Implement an integrated CRM system.

The activities must be executed over a longer time period, as the data migration, implementation of systems and roll-out take time. Based on estimations of the customer it will take approximately 5 years.

### 6.2.2 Case-Study 2

The overall outcome of the assessment of the current and desired maturity stage is provided in Figure 6.7. The blue cells show the current maturity stage and the green cell show the desired maturity stage. It can be seen that the current IT landscape is not yet at the same maturity stage, the production phase is still on a level 2 maturity. The desired maturity stage is set on maturity level 4. Similarly to the first case-study, the first goal is to include all the relevant elements and optimization might happen in a later stage but is not considered as relevant now.
In this case study, the high-level assessment based on the maturity table was not that straightforward. The enterprise grew mainly due to acquisitions of other companies across the globe. Therefore, the assessment of the entire organization led to a very scattered view. Within the organization, not all sub-organizations are at the same maturity stage. A recently acquired smaller company can be at stage one, while a well-established firm is already in the transition towards stage 4. For this reason, the assessment was scoped to one of the sub-organizations. This organization is responsible for a high percentage of the activities within the organization and is, therefore, a good focus area. Even though the assessment does no longer include the entire organization, it does provide a more concise insight. Note that when mentioning the enterprise in the remainder of the case study, it means the sub-organization unless explicitly stated otherwise.

Based on the maturity table, the interviewee positioned the current IT landscape at an overall stage 3 maturity, vertical and horizontal integration. Only production is not on a level 3 maturity, autonomous production, which is also not an immediate need. As an OEM organization, the main production activity is the assembly of subsystems and sell the systems as a whole to the client. Often this does not include machines, but mainly manpower. Some small components that are always needed are produced 24/7 on the shop floor using machines. It might be beneficial to automate this process and only produce these elements when necessary based on the orders.

The results of the questionnaire were rather similar to the answers provided above. Many of the enterprise systems are already cloud-based, either in a public or private cloud and accessible enterprise-wide. The PLM system operates across the production and development department and connects to the ERP and MES system. For this situation, there are multiple production facilities and the production occurs at a global enterprise level, so for the entire organization, not the sub-organizations. The company is working towards a flexible routing of production within these different production facilities. The MES system can generate production orders, such that the people on the shop floor can produce efficiently. Some work cells can produce autonomously but they are not integrated with any of the higher level information systems. Therefore connectivity in the full manufacturing pyramid is not established. As was mentioned above it is questionable if this situation is necessary. First steps towards an integrated service lifecycle management are taken, although this still happens in an offline manner. A CRM system including a sales configurator is available. Furthermore, horizontal integration is supported by the SCM system. The SCM is thus positioned on an enterprise level. The enterprise is not service-oriented although it does provide the necessary services to their customers, their main purpose is still selling goods.

Based on the maturity models it could be determined that there are two elements missing in the current assessed maturity stage, the service lifecycle management system and the fully integrated manufacturing pyramid. The latter is already discussed, but the first is a focus point for the enterprise. A SLM can help to transform the company towards a more service-oriented organization. The assessment of the AS-IS situation led to the visualization shown in Figure 6.8.
Step 2

Based on the information in Table 6.1, the desired situation is positioned at stage 4, full digitization. This is mainly triggered by the desire to integrate the entire lifecycle, stretching towards the integrated customer, and an established value network with partners. Currently, information on the product in use is captured in the PLM system. This information is static and offline and needs to be adapted manually based on reports. This is mainly product types or maintenance information. It would be beneficial to record real-data from the product in use, such that on an enterprise level relevant analysis can be performed. These analyses can be executed to improve product design, fast innovation cycle, or predictive maintenance. Furthermore, scalability and standardization were of importance such that a global approach can be used. Therefore, a global PLM and ERP system is necessary such that orders can be automatically distributed across the various production facilities, this leads to connected smart factories. As supply chain and demand planning are decided upon globally it is important that the systems are also standardized globally, to ensure agility, productivity, and quality. An integrated PLM in the cloud can help to provide this standardization and ensure the sustainability of the products. Lastly, there are opportunities to establish a collaborative value network that enables an autonomous supply chain. An autonomous supply chain responds to data aggregated from the work cell level. Based on changes in the design, inventory or product status, relevant supply chain information can be generated. This can be an automated order or changes in spare parts. The integration also stretches towards the customers, such that product configurations are automatically processed. The red marks in Figure 6.9 are the focus areas for maturity level 4.

Step 3 will not be discussed explicitly here, as the gaps are already represented in the visualizations of step 1 and step 2. Furthermore, the gaps are also addressed during the roadmap design. The gap analysis can be found in Appendix H.
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Figure 6.9: TO-BE situation case-study 2

**Step 4**

A summary of the roadmap containing the main activities is provided here. A more elaborate version can be found in Appendix H. The roadmap is based on the results from step 1 and 2. The company needs to move from a stage 3 maturity towards a stage 4 maturity.

- **Activity 1** Implement digital service lifecycle management.
- **Activity 2** Establish the digital product and production twin, by building simulation models and creating data analytics models.
- **Activity 3** Standardize the PLM system and ERP system so they are globally accessible, for the entire organization.
- **Activity 4** Develop Smart Products.
- **Activity 5** Make the PLM system accessible to the suppliers.
- **Activity 6** Implement a SCM system on a network level.
- **Activity 7** Implement an integrated CRM system.

### 6.3 Conclusion on Implementation Results

The implementation of the framework was successful in both case studies. All the steps of the approach could be executed and both times it led to the creation of the roadmap, the final result of the framework implementation. Both participants mentioned that the result was valuable. For company 1 it provided insights into the elements that are still missing in both their current and desired situation. For company 2 it mainly confirmed their vision and the correctness of their approach towards the future. Both companies vary a lot in their current maturity state. Company 1 is a start-up and some processes are still at maturity stage 1, while company 2 is already moving towards maturity stage 4. For this reason, they are two interesting case-studies as two extremes are analyzed that both recognize their own value in the application of the framework.
It must be noted that the second case-study had to be adjusted to make the implementation feasible. Therefore, the assessment could not be executed for the entire organization, but only for a sub-organization. Nevertheless, the result of the assessment was still valuable. The current situation as it was assessed, was already at stage 3 and is also the level that the outside world expects from this company. However, when acquiring a new and smaller business, it is likely that their maturity is not anywhere near stage 3. The framework can then be used to assess the maturity of this sub-organization and provide a roadmap to bring it to the same stage as the main organization. From that stage, all the sub-organizations can move on towards the set desired state of the whole organization. This way the framework can be used as an internal tool for smart manufacturing development.

The framework allows leaving aspects out of scope when they are not considered relevant. In case-study 1 the lower hierarchy levels, work-cell, and production line, in the development and usage/service phase were considered irrelevant for the company. Nevertheless, the assessment for the AS-IS and TO-BE situation is still relevant to the remaining aspects.

For a company with a greenfield starting point, the overview the framework offered was deemed very valuable. During the implementation of the framework, some key points that are quite important to support the development of the company were recognized. The approach also led to important insights for Atos, as it recognized several opportunities where they could support the company. For example, it was pointed out that the company still needs a MOMS and Atos can help to define functionalities of this system.

Both participants asked questions on what a certain step would provide in terms of business value for the company. According to Participant 2, the framework is very pragmatic and shows the key aspects of both a high-level and an applicable level. However, it would have contributed to the approach if business cases could be connected to a certain maturity stage. For example, if a successful use-case can be shown in which a smart factory was established implemented a smart factory, the benefits of this implementation can be shown. This makes it easier for a company to visualize a certain scenario and to identify if implementing certain systems would be beneficial for the company.

It is difficult to conclude anything on the general applicability of the framework, as the implementation approach was only executed twice. It can cautiously be concluded that the framework approach works, as the result was successful twice and it is fair to say that it was not just beginners luck the first time. What also argues in favor of the framework is that the cases were very different and that the general approach was successful for both. Even though the value created for the companies was different, both companies agreed upon the importance of the framework.
Chapter 7

Evaluation

In this section, the Smart Manufacturing Framework is evaluated based on its relevance. The relevance of the SMF is directly evaluated by the participants after the implementation of the framework. The evaluation approach that is used is based on the criteria of Shrivastava (1987). According to Shrivastava (1987), the practical usefulness of the solution design, the smart manufacturing framework, can be assessed by five criteria: (1) Meaningfulness, (2) Goal relevance, (3) Operational Validity, (4) Innovativeness, and (5) Cost of implementation. An explanation of these criteria is presented in Table 7.1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meaningfulness</td>
<td>The framework is meaningful, easy to understand and enhances problems relevant for a discrete manufacturer</td>
</tr>
<tr>
<td>Goal relevance</td>
<td>The framework adheres goals that are relevant for a discrete manufacturer</td>
</tr>
<tr>
<td>Operational Validity</td>
<td>The framework provides clear actions</td>
</tr>
<tr>
<td>Innovativeness</td>
<td>The framework surpasses common solutions and provides new practical insights</td>
</tr>
<tr>
<td>Cost of implementation</td>
<td>The framework shows feasible solutions in terms of costs and time.</td>
</tr>
</tbody>
</table>

The participants were asked to answer several open questions based on the five criteria. Furthermore, the evaluation also included a Likert-scale questionnaire ranking from 1, not at all satisfied, i.e. this criterion was not met at all, to 5 completely satisfied, i.e. the framework discussed this criterion completely. Each of the elements that must be ranked is related to one of the five criteria. Note, that the criteria were explained to the participants and the open questions also served to indicate the meaning of the criteria. The complete evaluation method is presented in Appendix I. The overall results are shown in Table 7.2.

7.1 Evaluation Results

In general, the smart manufacturing framework was positively received by the participants in terms of meaningfulness, goal relevance and cost of implementation. The implementation approach was evaluated as very understandable. It also provides an adequate overview of issues that are currently relevant in the manufacturing industry. The frameworks meaningfulness scored high for both interviewees.

The stages were considered to be feasible. Both participants even mentioned that the assessed TO-BE situation is not something they would like to reach but rather a mere necessity. For both participants, it was possible to see the roadmap to be implemented within a certain time frame. The expected costs and time are not included in the framework as it depends on the activities that are necessary to reach the desired maturity stage. However, this was not considered to be a pitfall of the framework because the solutions showed were deemed reasonable.

The results for goal relevance showed interesting differences between the participants. Company 1 rated this criterion as completely satisfied, while company 2 evaluated goal relevance as moderately satisfied.
For company 1 the to-be situation was very clearly visualized and helped to create a better understanding of the future situation, hence the high score. Company two already had a clear vision of the future situation and would rather have seen a clearer link to the relevant business cases, hence the average score. Overall both participants mentioned that the goal that was set related to the strategic goals within the company. However, a link to managers’ goals and business value could improve the goal relevance.

Action implications, i.e. operational validity, were less clear. Indeed the SMF remained conceptual in nature and thus scored high on the element conceptual. Note that the roadmap including the activities was sent to the participant after the evaluation. Nevertheless, the activities described in the roadmap are also still on a high abstraction level. The overall approach is clear, the outcome of the framework can be put into practice, but it is lacking really specific solutions. In order to determine clear and accurate activities a very specific set of knowledge is necessary, which was not in the scope of this project.

The smart manufacturing framework was ranked slightly above average on the innovativeness criteria. Especially the approach of the framework was perceived innovative by both of the participants, as it showed a combination of high-level, process aspect and pragmatic, integrated aspect, functionalities. However, the participants also mentioned that the solutions that are provided are not new solutions and therefore do not transcend the commonsense solutions. Nevertheless, the solutions that are provided were considered to give important insights into practical problems that are relevant for the participants at this moment.

Table 7.2: Evaluation results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Result</th>
<th>Average Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meaningfulness</td>
<td>The framework was considered very relevant and meaningful for the participants.</td>
<td>Very Satisfied (4)</td>
</tr>
<tr>
<td></td>
<td>The framework provides insights in the road towards the future situation and aligns the current situation and the visions.</td>
<td>Very satisfied (4)</td>
</tr>
<tr>
<td>Goal relevance</td>
<td>The framework provides relatively clear activities in the roadmap, but it is limited due to the conceptual nature, which makes implications not always clear</td>
<td>Moderately satisfied (3)</td>
</tr>
<tr>
<td>Operational Validity</td>
<td>The framework elements are not innovative and are marked as common sense solutions, however the framework approach and roadmap due present innovative insights.</td>
<td>Moderately satisfied (3)</td>
</tr>
<tr>
<td>Innovativeness</td>
<td>The framework shows feasible solutions that must be met within a certain time frame, but does not present the actual costs and time.</td>
<td>Very satisfied (4)</td>
</tr>
</tbody>
</table>

7.2 Conclusions and Recommendations for Atos

Based on the evaluation of relevance a few conclusions can be drawn that lead to recommendations for Atos.

First, the Smart Manufacturing Framework was received positively by the participating companies. The practical usefulness of the framework is considered high. The framework is considered very relevant as it visualizes a topic that is an important point on the agenda for both participants. Both companies extracted a different value from the framework. For the startup, the goal visualization is a great advantage of the framework. Visualizing the goal and determining a path towards that desired situation helps to extend their limited IT landscape. The manufacturer that already has a well-established IT landscape and smart manufacturing vision found it valuable that the framework puts it in perspective. It visualizes the situation and shows if you are on the right track to progress the smart manufacturing journey. Lastly, the pragmatic approach and feasibility were received positively. Due to its commonsense solutions, it is
clear what needs to happen. The interoperability of known systems can be used to cover most activities that need to occur to fulfill smart manufacturing capabilities. Because the participants were already acquainted with the systems, the feasibility of the approach was assured.

The commonsense solutions and visualization of known and acknowledged software systems do lead to a lower score on the innovativeness of the framework. The goal of the framework was mostly to show the interoperability of the systems. Only if the architecture is correct relevant information can be extracted from the large amounts of data that constantly moves through the systems. Only when this happens optimized decision-making and automatization can happen and new technologies become valuable.

The concreteness of the framework was considered low mainly due to the conceptual nature of the framework. The conceptual approach helps to have a more general framework that is applicable to various situations, but it is harder to see its implications. Both participants would have rather seen the direct implication of activities and more concrete activities. Activities can be extracted from the maturity models directly when creating the roadmap, but they were still considered to be on a high abstraction level. Furthermore, the goal relevance and concreteness of the system can be improved, by including business cases. Within Atos, projects are already executed that can be integrated with the framework. Connecting these use cases to a certain maturity stage or activity shows an accurate result. More importantly, it provides insight into the business value that an activity can provide and helps to decide whether or not the activity is relevant.

Based on these conclusions three recommendations for Atos are distinguished.

First, when a company is involved in smart manufacturing practices or wants to orientate itself in this field, use the Smart Manufacturing Framework as one of the best practices. The framework includes aspects that are relevant for each manufacturer that wants to keep up with new innovations. The framework visualizes a complex ecosystem in an understandable and pragmatic manner and is well received by the clients.

Secondly, use the framework as a tool to establish new projects. The framework provides a standardized manner to identify gaps within the current landscape. This shows directly new opportunities for Atos to step in and show the possibilities to fill in those gaps. Long-term projects can be established once the company starts its smart manufacturing journey and follows the designed roadmap. Using the roadmap long-term projects can be established, where organizations must be guided along their smart manufacturing journey.

Third, make the framework more concrete during the implementation. The Atos employees possess the necessary knowledge, to directly come up with concrete solutions. The concrete solutions go beyond establishing that a Manufacturing Execution System is needed, but include types, functionalities, and an implementation approach. As this knowledge is available within the company, it would be good to implement it within the framework when it is used. Furthermore, include some business cases for each maturity stage that show the value and possibilities of a stage in an actual situation.
Chapter 8

Conclusion and Outlook

This chapter concludes the main results and reflects on the research as a whole. In addition, this chapter provides an overview of the added value for different stakeholders and indicates directions for future research.

8.1 Research Conclusion

During this project, a framework is created and analyzed to support the development of smart manufacturing. This artifact is the answer to the following research question that was based on the problem statement:

"How can technologies, capabilities, and activities belonging to smart manufacturing be structured, such that it creates new values for the manufacturing industry?"

The literature review provided a number of reference architectures for various initiatives within the fourth industrial revolution. The analysis of the reference architectures verified that currently there is a lack of reference architecture that helps to support the smart manufacturing paradigm. The existing architectures for smart manufacturing are not facilitating architectures, show a high abstraction level and do not include the technology aspect.

This analysis identifies the need for a complete, facilitating reference architecture that supports the development of smart manufacturing. Therefore, elements from the existing reference architectures are extracted and positioned on the independent reference framework AFIS. The AFIS framework is adapted to the fourth industrial revolution, based on the RAMI 4.0 framework. Positioning the elements leads to the design of the conceptual model as was shown in Chapter 4. The conceptual model provides an overview of the important characteristics of the smart manufacturing paradigm and has an integrated approach. The mapping on an independent framework proposes a unified model that provides users with a central value. However, the conceptual model is still not facilitating the development of smart manufacturing. The conceptual model only provides a complete overview of the elements that are necessary within an enterprise but does not show any activities how to get to that desired state. Therefore, it can not be used as a tool by Atos to identify the opportunities for their clients.

A new design iteration is executed to change the conceptual model into an operational model. The conceptual model is extended by maturity stages and aspects of the modernized Truijens Framework. The aspect dimension is made implicit to reduce the four-dimensional space to a three-dimensional space showing the hierarchy layers, lifecycle phases, and maturity stages. The resulting Smart Manufacturing Framework shows five maturity stages based on the SIMMI 4.0 maturity model. Each maturity stage is designed as a self-contained model based on the aspect dimensions plus an additional integration view. The result of the operational Smart Manufacturing Framework is a tool, consisting of 20 models, that helps to assess the current IT landscape and define the desired state. The framework is not yet complete as for example the data and organization aspect are missing. Furthermore, important technologies such as additive manufacturing, virtual reality, and artificial intelligence are not explicitly covered in the framework. These technologies are not key technologies that are necessary to develop smart manufacturing but can provide additional value to enterprises.

The implementation of the operational Smart Manufacturing Framework showed that the tool can be
successfully used in practice. For both case-studies the final result, the roadmap could be constructed, based on the maturity models. During the implementation, the framework was validated by using several methods to reach the same result. This approach showed that the Smart Manufacturing Framework was correct and recognizable for the participants. The two case studies were two extremes, a start-up and a well-established OEM, which provided insights into both sides of the spectrum. This also led to a different type of value that was gained from the framework. For the startup, it was especially interesting to see the growth that they still had to go through and it provided new insights on what functionalities they needed for their production environment. On the other side of the spectrum, the participant already had a clear vision of the activities they had to perform to get from stage 3 to stage 4. Nevertheless, it was valuable for this participant to have a reminder of the activities that still needed to be performed and a confirmation that they are on the right track to fully establish smart manufacturing capabilities.

The limited number of case-studies does make it difficult to say anything about the general applicability of the framework. The implementation succeeded twice, so it was not just beginners luck, but it might be the case that the approach needs to be changed in other situations. Nevertheless, every manufacturer needs an IT infrastructure, to support their product development or production phases (Weber et al., 2017). The outline of the framework is designed using standards, such as ISA-95 and product lifecycles, that can be applied to any enterprise within the manufacturing industry. Therefore, the design is not specific to a single enterprise. Furthermore, the framework covers standard information systems that are well-known in enterprises and applicable in the manufacturing industry. For example, every manufacturer that executes both development and production needs at least a PLM, ERP and MES system (Khedher et al., 2011). This makes the elements within the framework applicable to the entire manufacturing industry. The framework makes it possible to identify, which systems are available and which systems are still missing in any situation, due to its general elements. Therefore, it fulfills a business need that currently exists in the manufacturing industry, by showing the steps they have to take in order to apply smart manufacturing. By fulfilling that need the framework can bring value to the manufacturing industry as a whole. However, due to the limited case-studies generalizability, is not proven and it is not certain that the framework provides new value. The result of the framework implementation was positive and also showed new possibilities for Atos. Therefore, it is recommended to Atos to include it in their best practices.

Not only the implementation of the framework gave a successful result, but the practical usefulness was also evaluated positively. The relevance of the framework is considered very high as it points out issues that the companies are currently coping with. Due to the visualization of well-known elements, the framework is recognizable and it gives a clear overall visualization of what needs to happen. For this reason, the framework was not considered to be innovative. It does not show elements that are new and therefore does not appear innovative. Nevertheless, the framework as a whole was considered to be innovative. The approach and architecture was something that the participants had not seen before. For example, the positioning of software elements along with lifecycle phases and a manufacturing hierarchy was considered innovative and the visualization of the maturity stages is also seen as a contribution. Furthermore, the high-level functionalities in the process aspects and the pragmatic view in the software aspect were considered new and useful.

8.2 Contributions

First, a contribution to literature has been made by designing a facilitating reference architecture for smart manufacturing. The analysis showed that there was still a gap in the literature to fill and this research has indicated that the Smart Manufacturing Framework does support the development of smart manufacturing. The design approach of extracting elements from existing references and mapping these to stages was not unique, but the result is considerably different. The visualization of the maturity stages based on aspects from the information systems domain is a new way to represent the capabilities that are needed for smart manufacturing. Furthermore, the framework contributes to a business need within the manufacturing industry. it untangles the complexity and provides a plan on how to reach a certain vision. The Smart Manufacturing Framework provides a pragmatic solution to create structure in a complex environment. It can be used as an internal tool by companies to create a roadmap for the entire organization.

Second, the conceptual model shows a unified view of the various elements positioned using a manufacturing standard and lifecycle phases. This research defines the relation between the hierarchy levels and
the three lifecycle phases, while often in this field of research the focus is limited to the production phase. The positioning of elements on a well-known hierarchy standard and for each lifecycle phase is new and provides an accurate view of the systems and functionalities available within the smart manufacturing paradigm.

Lastly, the SMF can also be used by external parties, more specifically consultants, to show possible solutions to bridge existing gaps. This contribution provides business value for Atos. The goal of the framework was for Atos to have a structured approach to provide their customers with new opportunities and guide their clients throughout their smart manufacturing journey. Firstly, when a customer is still in the orientation phase the tool can help to identify the desired situation and create a vision, what the enterprise wants to achieve with smart manufacturing capabilities. Once, this is established there lays an opportunity to engage in a long relationship and build the road together. Atos can provide solutions in the form of systems and techniques that brings the company closer their goal. This is beneficial for Atos because if they can show that they have solutions to fill in the existing gaps, a client is likely to engage in a mutual project. The SMF provides an opportunity for Atos to easily identify opportunities and show their own capabilities.

8.3 Reflection

A research project can not always go flawless, during this project some improvement points have been identified during the process. At the beginning of the project, a lot of effort was spent on keeping AFIS as it was. This meant that everything was kept the same, even the functionalities, and the elements of the reference architectures needed to be generalized to fit the framework. After experimenting with this approach at first, the results were interesting but not as desired. The results showed gaps in terms of functionalities but did not include any of the key elements of smart manufacturing. Therefore, the approach was changed and the AFIS framework is adapted to fit smart manufacturing features. It would have been better if the conclusion was drawn sooner and the current approach was started earlier in the research. This could have led to a more complete framework.

Not all aspects of the modernized Truijens framework are included in the Smart Manufacturing Framework. The decision to extend the model using a maturity model was made relatively late during the project. This led to decisions that must be made in order to ensure the feasibility of the project. A more complete framework would also include data analytics techniques, concrete data flows and an organizational model. An earlier decision to include the maturity models could have led to a more complete framework.

The number of case-studies can also be considered as a limitation for the generalizability of the implementation and evaluation. There were two companies considered to be fit for the implementation, from the perspective of Atos. For a better conclusion of the applicability of the framework for the entire manufacturing industry, more case-studies need to be performed.

The final result of the Smart Manufacturing Framework is evaluated during the case-studies, but not by the intended end-users within Atos. Evaluation and discussion moments took place during the design of the framework, so input from Atos’ side is included in the design. This is important to ensure the usefulness of the framework for Atos is guaranteed. However, to support that the framework will be used by Atos, it is better to have a workshop to show the implementation and possible results. This workshop includes an explanation of the Smart Manufacturing Framework and the relating maturity models, so they aware of the content. It explains how the SMF can be used at the clients showing the implementation approach, so the end users know how to apply it. And lastly, it shows concrete results of the case studies to emphasize the value and possibilities for Atos. This approach should create awareness at Atos for the framework and encourage people to start using it.

8.4 Future Research

First, to enhance proof for the generalizability of the Smart Manufacturing Framework it is recommended to implement the framework in more case studies. It would be beneficial if the framework would also be implemented by a real manufacturer with a high throughput of products, to have a different perspective than the ones in this research.
There are two extensions possible for the Smart Manufacturing Framework. First, the remaining aspects, the data aspect, and organizational aspect can be included in the framework, such that all aspects for implementing smart manufacturing are covered and a complete roadmap can be designed. Second, relevant business cases can be included in the smart manufacturing framework, to make it more concrete. Projects that Atos already executed, can be connected to a maturity stage. This makes the outcome and value of a certain activity or stage clearer. For example, build a portfolio of template cases that directly relate to the implications.
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Participant1. (2019). Personal interview. Conducted on April 1st and available on request.

Participant2. (2019). Personal interview. Conducted on April 15th and available on request.


On the road towards Smart Manufacturing


Appendix A

Design Science Research (DSR) Paradigm

The DSR paradigm consists of the original framework and is later extended by the three research cycles (Hevner, 2007) and a knowledge contribution framework (Gregor & Hevner, 2013). The visualization of these three frameworks is shown in Appendix A.1, A.2 and A.3.

Information Systems Research Framework

The Framework for design science research showing the balance between rigor and relevance is shown in A.1

![Information Systems Research Framework](image)

Figure A.1: Information Systems Research Framework (Hevner, March, Park & Ram, 2004)
Three research cycles

The three research cycles from Hevner (2007) are visualized in A.2.

![Three Research Cycles](image)

Figure A.2: Three Research cycles (Hevner, 2007)

The knowledge contribution framework

The knowledge contribution framework from Gregor and Hevner (2013) is shown in A.3

![Knowledge Contribution Framework](image)

Figure A.3: Knowledge contribution framework (Gregor & Hevner, 2013)
Appendix B

Results from literature review

The visualization of the architectures, discussed in Section 3.1 and a short explanation of the elements are presented here. Note that these are the results of the literature review previous to this research project (Brouns, 2019).

ISA-95

The description of the levels is based on American National Standard (2005), Jiang (2018)

- **Level 0** the physical process;
- **Level 1** contains activities for sensing and actuating the physical process of level 0;
- **Level 2** contains activities that monitor and control the physical processes. A possible entity can be a supervisory control and data acquisition (SCADA) system.
- **Level 3** defines workflow activities to support the production process, for example maintaining the records. A possible entity can be a manufacturing execution system (MES).
- **Level 4** runs the enterprise and contains business related activities such as planning and scheduling. A possible entity can be an enterprise resource planning (ERP) system.

![ISA-95 framework](image)

Figure B.1: ISA-95 framework (American National Standard, 2005)

5C & 8C Architecture

The description of the 5C elements is based on Lee et al. (2015) and the 8C facets on Jiang (2018).

- **Connection** extracts data from the physical environment using its sensor network or manufacturing systems;
- **Conversion** retrieving information from the extracted data by executing some small data analysis;
- **Cyber** is the central information storage, containing data from various machines. Which allows it to create a digital twin of the machines. Using this information autonomous learning and process predictions can be established;
APPENDIX B. RESULTS FROM LITERATURE REVIEW

Figure B.2: 5C (Lee, Bagheri & Kao, 2015) and 8C (Jiang, 2018) Architecture.

- **Cognition** uses the acquired knowledge to support the decision making for future process optimization. Visualization of data can play an important role to transfer the knowledge;
- **Configuration** transfers feedback from the cyber space to the physical world such that the system acts upon the decision that are taken. This level acts as supervisory control to make machines self-adaptive.
- **Coalition** integration different parties along the value and production chain to jointly build a supply chain in a flexible way; am
- **Customer** focuses on the role of a customer along the lifecycle from the design until the after-sale. This is necessary for the emerging mass customization demand of customers;
- **Content** enhances the traceability and performance of the product across the lifecycle as all the data of the product is stored and analyzed along the process

**RAMI 4.0**

The description of the RAMI elements is mainly based on (VDI/VDE, 2015). The hierarchy levels are based on American National Standard (1995, 2005) and the definitions of the vertical layers from Frysak et al. (2018) are used.

- **Hierarchy Levels** represents the functionalities within factories and is based on the ISA-95 standard, adding some additional elements to enhance the Industry 4.0 environment.
  - **Product** is the manufactured product itself;
  - **Field Device** is considered to be an intelligent device such as a smart sensor;
  - **Control Device** combination of sensors and actuators that carries out basic control;
  - **Station** can carry out minor activities and is made up of multiple control modules;
  - **Work Centers** can produce multiple items and execute a combination of methods and techniques;
  - **Enterprise** is responsible for the planning of multiple factory sites;
  - **Connected World** describes the collaboration with suppliers and customers.

- **Life Cycle** is based on the standard for life-cycle management. It makes a distinction between type and instance.
  - **Type** shows the basic idea of the product and covers the development and maintenance phase;
  - **Instance** describes the concrete assets and consists of the manufacturing, usage and maintenance of the object.

- **Vertical Layers** present various viewpoints based on ICT standards. The layers help to breakdown a complex system into multiple smaller pieces.
APPENDIX B. RESULTS FROM LITERATURE REVIEW

- **Asset Layer** gathers data from material assets;
- **Integration Layer** gathers data from immaterial assets;
- **Communication Layer** includes communication protocols and enables communication processes;
- **Information Layer** includes the information model and relevant data;
- **Functional Layer** provides the horizontal integration and formal description of platforms;
- **Business Layer** regulates the business processes.

![RAMI 4.0 Framework (VDI/VDE, 2015)](image)

**Smart Manufacturing Ecosystem**

The description of the elements is based on the article by Lu, Frechette and Morris (2016).

- **Manufacturing Pyramid** allows the vertical integration of machines, factories and systems. To enhance self-awareness and self-correction among the factory it is important that information flows through the pyramid;

- **Product lifecycle** starts at the product design and ends with the end-of-life of a product, including 6 phases. One of the phases, manufacturing, is represented by the manufacturing pyramid;

![Smart Manufacturing Ecosystem (Lu, Frechette & Morris, 2016)](image)

- **Production lifecycle** consists of 5 phases beginning with the design until the decommissioning of the production facility. During their lifecycle the production systems are reconstructed to allow for new products to be produced. This requires a certain amount of flexibility in the design of the production systems;

- **Business lifecycle** enhances the interaction between supplier and customer, through the source, plan, make, and deliver phases. As customer demands change faster and ask for personalized products it is important that information flows through the lifecycle such that adaptions can be made quickly.
APPENDIX B. RESULTS FROM LITERATURE REVIEW

APPENDIX B. RESULTS FROM LITERATURE REVIEW

Figure B.5: Industrial Internet reference Architecture (Lin et al., 2017)

Industrial Internet Reference Architecture

The description of the viewpoints are based on the report by Lin et al. (2017)

- **Business viewpoint** is concerned with the identification of stakeholders and their visions in the business context. The state of the objectives is identified through mapping on fundamental capabilities;

- **Usage Viewpoint** represents activity flows involving both human and logical users, trying to achieve the key functional capabilities;

- **Functional viewpoint** shows the functional components and the interaction and relationships between these components. These can be both within the system as well as in the external environment;

- **Implementation viewpoint** considers the technologies needed to implement components from the functional layer. These elements coordinate activities in the usage viewpoint and support the objectives of the business viewpoint.

Software-Defined IIoT Architecture

The descriptions result from the article by Wan et al. (2016).

- **Physical Layer** is composed of various devices such as sensors and various networks. The nodes in these networks can correspond in real-time and information is send to the control layer.

- **Control Layer** realizes the communication between the physical and application layer. The control layer sends information to the physical layer to control the physical assets and make adjustments based on their performance. Information about the performance of the equipment is corresponded to the application layer.
• Application Layer can display various applications that for example show the performance of the machines. Information in this layer can be analyzed such that processes on the lower layers can be improved and performance is optimized.

Internet of things Architecture Reference Framework

The description of the components is based on the report by Bauer et al. (2013).

• IoT Process Management incorporates traditional process management into the IoT world. This included both modelling and execution of processes.

• Service Organization enables the communication between the various facets, via services as it is the primary form of communication in IoT-ARF. This included the orchestration, composition and choreography of the services.

• Virtual Entity provides interaction with the IoT system based on the virtual entity, which is a digital representation of the physical entity. It manages associations for services and other virtual entities.

• IoT service contains IoT services and enables discovery and look-up of various IoT services. An IoT service can be used to collect and deliver data via the network.

• Communication provides a common interface for the IoT services and provides a platform for the variety of interaction schemes of the IoT systems.

• Security ensures the security of the IoT platform based on, authorization, trust, key exchange, identity management and authentication.

• Management is responsible for cross-functionality between the various IOT systems. The management facet considers, configuration, fault, reporting, member and state. It connects the various concepts, facets and members of the IoT system. Furthermore, it keeps track of the state, as well as faults and configurations of these aspects.

Figure B.7: IoT-ARF (Bauer, Boussard, Lucent, Bui & Carrez, 2013)
Appendix C

Analysis of frameworks

Table C.1 shows the sub-dimensions and the corresponding criteria. The reference architecture types and their corresponding values are shown in Table C.2. Lastly, Table C.3 provides the results of the analysis of the frameworks.

Table C.1: Multi dimensional space for reference architectures (Angelov et al., 2012)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Sub-Dimension</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Context</td>
<td>C1: Where will it be used?</td>
<td>Single-Organization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multi-Organization</td>
</tr>
<tr>
<td></td>
<td>C2: Who defines it?</td>
<td>Software Organization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>User Organization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Independent Organization</td>
</tr>
<tr>
<td></td>
<td>C3: When is it defined?</td>
<td>Preliminary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Classic</td>
</tr>
<tr>
<td>Goal</td>
<td>G1: Why is it defined?</td>
<td>Standardization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Facilitation</td>
</tr>
<tr>
<td>Design</td>
<td>D1: What is described?</td>
<td>Components and Connectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Protocols</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Algorithms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Texture</td>
</tr>
<tr>
<td></td>
<td>D2: How detailed is it described?</td>
<td>Detailed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Semi-detailed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aggregated</td>
</tr>
<tr>
<td></td>
<td>D3: How concrete is it described?</td>
<td>Abstract</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Semi-concrete</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>D4: How is it represented?</td>
<td>Informal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Semi-formal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Formal</td>
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</table>
### Table C.2: Overview of the reference architecture types and their corresponding values

<table>
<thead>
<tr>
<th>Type</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
<th>Type 5</th>
</tr>
</thead>
<tbody>
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<td>Single</td>
<td>Multiple</td>
<td>Single</td>
<td>Multiple</td>
</tr>
<tr>
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<td>Independent</td>
<td>Software</td>
<td>Research Center</td>
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<tr>
<td>G1</td>
<td>Standardization</td>
<td>Standardization</td>
<td>Facilitation</td>
<td>Facilitation</td>
<td>Facilitation</td>
</tr>
<tr>
<td>D1</td>
<td>Components</td>
<td>Components</td>
<td>Components</td>
<td>Components</td>
<td>Components</td>
</tr>
<tr>
<td></td>
<td>Interfaces</td>
<td>Interfaces</td>
<td>Texture</td>
<td>Algorithms</td>
<td>Protocols</td>
</tr>
<tr>
<td>D2</td>
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<td>Aggregated</td>
<td>Aggregated</td>
<td>Aggregated</td>
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<tr>
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<td>Detailed</td>
<td>Semi-detailed</td>
<td>Semi-detailed</td>
<td>Detailed</td>
<td>Detailed</td>
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<td>Semi-concrete</td>
<td>Concrete</td>
<td>Concrete</td>
</tr>
<tr>
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<td>Semi-formal</td>
<td>Semi-formal</td>
<td>Formal</td>
</tr>
<tr>
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<td>Semi-formal</td>
<td>Informal</td>
<td>Semi-formal</td>
<td>Semi-formal</td>
</tr>
</tbody>
</table>

### Table C.3: Overview of the identification of the RA dimension values

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<tr>
<th>Dimension</th>
<th>5C</th>
<th>RAMI</th>
<th>SME</th>
<th>IIRA</th>
<th>IIoT</th>
<th>IoT-ARF</th>
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<tr>
<td>Context</td>
<td>C1</td>
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<td>MO</td>
<td>MO</td>
<td>MO</td>
<td>MO</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>IO</td>
<td>IO</td>
<td>IO</td>
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</tr>
<tr>
<td></td>
<td>C3</td>
<td>Classic</td>
<td>Classic</td>
<td>Classic</td>
<td>Classic</td>
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</tr>
<tr>
<td>Goal</td>
<td>G1</td>
<td>F</td>
<td>S</td>
<td>S</td>
<td>F</td>
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</tr>
<tr>
<td>Design</td>
<td>D1</td>
<td>Component</td>
<td>Component</td>
<td>Component</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Texture</td>
<td>Interfaces</td>
<td>Interfaces</td>
<td>Interfaces</td>
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<td>Texture</td>
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<td>Texture</td>
<td>Texture</td>
<td>Texture</td>
</tr>
<tr>
<td></td>
<td>D2</td>
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<td>Informal</td>
<td>Informal</td>
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</tr>
</tbody>
</table>
Appendix D

The Three-dimensional Design Cube

A visualization of the three-dimensional design cube with the different levels as was mentioned in Section 4.3 is provided in Figure D.1.

![Figure D.1: Three-dimensional design cube, based on Grefen (2016b)](image)

**Aggregation dimension**

The aggregation dimension determines the level of detail, based on the number of components that are identified in the design. An example is given in Figure D.2. The levels are defined as follows:

- Level 1 is a single component, also known as blackbox;
- Level 2 sub-systems that show a high-level architecture structure;
- Level 3 components are available within the main architecture structure;
- Level 4 components are decomposed into sub-components.

![Figure D.2: Visualization of the aggregation levels](image)
Abstraction dimension

The abstraction dimension determines the concreteness of an architecture. The elements in an architecture can be either general or precise. An example of abstraction levels is visualized in Figure D.3. The abstraction levels are defined as follows:

- Level 1 the class type of the component indicates the functionality, general software system;
- Level 2 system type components specify a certain type of system that supports the level 1 functionality;
- Level 3 system components are vendor specific.

![Figure D.3: Example of abstraction levels](image)

Realization dimension

The realization dimension defines the orientation of the architecture. This can range from technology oriented to business oriented (Grefen, 2016b). The BOAT framework is used for the realization levels, shown in Figure D.4.

- Business (B) contains the business goals and answers to why a certain architecture exists. It does not consider how things are done;
- Organization (O) describes the structure of organizations. This mainly consists of business processes and organization structures;
- Architecture (A) this level actually includes information systems and shows the software structure to support the organizations;
- Technology (T) depicts concrete ingredients, such as protocols and software, to describe the technological realization of the architectures specified at the architecture level.

![Figure D.4: Example of realization dimension, taken from Grefen (2016a)](image)
Appendix E

Setup semi-structured interview

Note, in case the interviewee was not familiar with the project, a brief introduction regarding the project was provided by prepared slides.

The goal of the interview was to get an overview of the current status of Industry 4.0 practices within Atos. Furthermore, a first evaluation of the designed framework was done during this interview. Especially the relevance of the framework and the goal for an Industry 4.0 tool, should result from the interviews. Depending on the expertise of the interviewee the answers and results can differ. The following questions were asked.

Current status of Industry 4.0 practices at Atos

1. Which solutions for Industry 4.0 does Atos currently provide?
2. What are current best practices for Industry 4.0 within Atos?
3. What type of tool would be useful for Atos?
4. What would be the goal of this tool?

Brief framework evaluation

1. Are the elements in the framework recognizable?
2. Is the framework self-evident?
3. Would the framework be useful as a tool for Atos?
4. Which aspects should be adapted to serve Atos better?
## Appendix F
### Maturity Models

<table>
<thead>
<tr>
<th>Maturity Model</th>
<th>Objective</th>
<th>Focus</th>
<th>Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM³E (Mittal, Romero &amp; Wuest, 2018)</td>
<td>Support Small and Medium sized enterprises throughout the digital journey</td>
<td>SME companies</td>
<td>5</td>
</tr>
<tr>
<td>Maturity Model Industry 4.0 (Schumacher, Erol &amp; Sihn, 2016)</td>
<td>Assessing industrial enterprises in discrete manufacturing based on 9 organizational dimensions</td>
<td>Multiple organizational dimensions</td>
<td>5</td>
</tr>
<tr>
<td>Industry4.0-MM (Gökalp, Şener &amp; Eren, 2017)</td>
<td>Provide a common base for performing an assessment of the establishment of Industry 4.0 technologies</td>
<td>Multiple organizational dimensions</td>
<td>6</td>
</tr>
<tr>
<td>Acatech-Industrie 4.0 Maturity Index (Schuh, Anderl, Gausemeier, ten Hompel &amp; Wahlster, 2017)</td>
<td>Offer enterprises practical guidance for developing and implementing an Industry4.0 strategy</td>
<td>Multiple organizational dimensions</td>
<td>6</td>
</tr>
<tr>
<td>SIMMI4.0 (Leyh, Bley, Schäfer &amp; Forstenhäsler, 2016)</td>
<td>Classify a companies’ maturity based on the four main requirements of Industry 4.0</td>
<td>SMEs, mainly software landscape</td>
<td>5</td>
</tr>
<tr>
<td>Guideline Industrie 4.0 (Anderl et al., 2015)</td>
<td>Support small and medium sized German companies in identifying potentials in relation to Industrie 4.0</td>
<td>German SMEs</td>
<td>5</td>
</tr>
<tr>
<td>IMPUSLS-Industry 4.0 readiness (Lichtblau et al., 2017)</td>
<td>Assess the willingness of companies to implement Industry 4.0 ideas</td>
<td>German Mechanical Engineering Industry</td>
<td>3</td>
</tr>
<tr>
<td>Maturity and Readiness model for industry 4.0 strategy (Akdil, Ustundag &amp; Cevikcan, 2018)</td>
<td>Create a model that is suitable for planning and transforming their operations for Industry 4.0 considering a broad organizational perspective</td>
<td>Multiple organizational aspects</td>
<td>3</td>
</tr>
<tr>
<td>Smartness assessment framework for smart factories (Lee, Jun, Chang &amp; Park, 2017)</td>
<td>Assess the vision of the future factory incorporating information and communication technology based on the concept of operation management to fit the manufacturing industry</td>
<td>Smart Factory</td>
<td>5</td>
</tr>
<tr>
<td>Maturity Model for Data-Driven Manufacturing (M2DDM) (Weber, Königsberger, Kassner &amp; Mitschang, 2017)</td>
<td>Guide companies in adopting principles of I4.0 as well as criteria to meet the defined maturity stages</td>
<td>Smart factory</td>
<td>6</td>
</tr>
</tbody>
</table>
Appendix G

Smart Manufacturing Framework

The Smart Manufacturing Framework consists of 5 maturity stages. Each maturity stage consists of 5 maturity models that all display a different aspect dimension, process, software and platform aspects and an integrated model of the software and platform aspects showing the interoperability of the systems. As was already mentioned in Chapter 5, at least 225 design decisions are made during the process of developing the SMF. This appendix shows the 20 maturity models of the SMF and provides a short description of the design decisions that are made, including an argumentation. Not each argument is based on rigor or relevance, sometimes it was merely a gut feeling. In case it is the later I will try to describe my reasoning as accurate as possible.

Level 1 : Basic Digitization

The first maturity level represents a company that has not yet addressed Industry 4.0 activities. Digitization of the processes is limited or none existing.

Process Aspect

![Figure G.1: Process Aspect Basic Digitization](image)

- According to (Leyh, Bley, Schäffer & Forstenhäuser, 2016), there is no digital support for product development. Therefore, product information is scattered across the organization (Batenburg et al., 2006). The lack of digital support also suggests that there are no digital tools for product design. However, based on expert knowledge the is not the case in real-life. Hence, each divisions has its own development tool.
- The functionalities, plotted on site level and enterprise level, are based on the ISA95 standard
dimensions (American National Standard, 2005). The functionalities plotted on site level are all considered level 3 functionalities, while resource management is considered a level 4 functionality (Erasmus et al., 2018). For this reason, a distinction in positioning the functionalities on the hierarchy levels is made. Level 4 resembles the entreprise level and level 3 operates on level lower on the site level.

- It is assumed that the necessary manufacturing equipment is available on the shop floor and embedded with standard machine software. This enables partially digitized production support on a lower level. The traditional manufacturing pyramid is established. Therefore, production is planned on a site level and resources are planned on enterprise level (American National Standard, 2005). These systems are not integrated so the planning is shared with shop floor workers, such that the processes can be executed. In an agile environment this means that the workers have to make fast improvements based on the tons of data they receive, which is an almost impossible job (Weber et al., 2017).

- The company is not service oriented and therefore provides only limited support. There is no significant relationship with the customer (Park & Kim, 2003).

**Software Aspect**

![Software Aspect Basic Digitization](image)

- Software tools are available for the design of products, often they are split in three different categories M-CAD for mechanical, E-CAD for electrical and SWD for software development, based on (Lu, Frechette & Morris, 2016) and expert knowledge within Atos.

- The software systems on site level all take care of one of the functionalities mentioned in the process aspect. As the organization is still siloed, individual systems are implemented.

- Production is supported by a Programmable Logic Controller (PLC) on the work cell level. This is a remote terminal unit, that due to the programming capabilities has established a more sophisticated manner of monitoring and control (Endi, Elhalwagy et al., 2010). The PLC is a common practice in current industrial systems and provides a real-time operation, based on its connection with sensors and actuators as well with higher level SCADA systems (Tomlein & Grønbæk, 2017).

- Batch Sequential data flow between SCADA and some of the information systems (Grefen, 2016b). Continuous and anytime data availability can not be ensured (Leyh, Bley, Schäffer & Forstenhäuser, 2016).
Platform Aspect

A fieldbus enables the connection between SCADA and PLC and is a standard element in the manufacturing industry. A field bus is an umbrella term for standards such as MODBUS and TCP/IP (Endl, Elhalwagy et al., 2010). This connection can be either hardwired, point to point, or via radio.

Integrated Aspect

Figure G.4: Integration of software and platform aspect Basic Digitization
Level 2: Cross-Departmental Digitization

Individual departments are now digitally supported. Industry 4.0 activities are present across the enterprise. However, data exchange is not automated across departments, therefore the activities are still partially decentralized.

Process Aspect

- Data is integrated within the departments, this means that all the different systems within the departments are integrated. The SIMMI 4.0 model stage descriptor, cross-departmental digitization, suggests full digitization between departments. However, the description of the stage mentions partial digitization between departments (Leyh, Bley, Schäffer & Forstenhäuser, 2016). Based on discussions with experts it is decided that automated information sharing happens within departments, but that the connection to other departments is still offline. This is an important assumption made, based on the real-life situations these experts experienced.

- No automated data exchange between departments, therefore still partially decentralized

- One step closer to the smart factory so communication between machines and self-aware production lines are available. Self-awareness is the second level in the 5C-architecture and suggests data conversion of multiple machines to execute basic analysis such as prognostics and health management (Lee et al., 2015).

Software Aspect

- Integrated system for manufacturing Manufacturing Operations Management System (MOMS) that integrates all the functionalities displayed in stage 1. It is discussed that an elaborate MES system can handle all the various functionalities. However, for clarity we visualize it as an independent integrating system (Erasmus et al., 2018).

- The Business Process Management System (BPMS) helps to orchestrate the activities from the various information systems within the MOMS (Erasmus et al., 2018). This ensures the efficient execution of activities. This approach is based on the architecture of the HORSE project (Grefen, Vanderfeesten & Boultadakis, 2016b). The Horse software supports the actual manufacturing processes and thus connects the information systems on site level to the machines and employees on work cell level.
The new technology stack of Porter and Heppelmann (2014) shows that software must be embedded in the things, in this case the machines on a work cell level. This IoT software embedded in the machine, requires sensors and actuators embedded in the machines to generate the data.

Customer database is established, information can be accessed by file transfer. No analysis are made based on the information on the customer, which means that there is no added value created based on relationship management (Park & Kim, 2003).

PLM system is established for the development department. It is mainly seen as a product data management tool that can push some of the information to the production department. Production engineering is executed locally within the MOMS (Batenburg et al., 2006).

Systems engineering software covers the development of total systems. In other words it lays down the structure of a product based on customer requirements. As it integrates the various types of components and provides the basis for the development of the entire product, the systems engineering software is positioned on the production line level. (Albert & Mirko, 2007; CMMIteam, 2001)

The data of an entire product is managed in a product base on site level, as at the end of production in the factory a certain product is delivered. In most cases a PDM is not necessary when a PLM is available as all product-information is stored in the PLM. However, to provide a complete overview of the possible systems on the various hierarchy levels the PDM is included in the model.

Figure G.6: Software Aspect Cross-departmental digitization
Platform Aspect

- Workcell and production line in the production department are connected by a fieldbus (Endi, Elhalwagy et al., 2010).

- The component data is no longer siloed, but are stored in one central database. All the different design tools can access that database to open the files they need, this is known as a shared repository (Grefen, 2016b). A shared data storage also supports the congruence between the various components.

- The manufacturing activities on site and the business process management system responsible for the manufacturing processes, are connected via an ESB (Erasmus et al., 2018).

![Platform Aspect Cross-Departmental Digitization](image)

**Figure G.7: Platform Aspect Cross-Departmental Digitization**

Integrated Aspect

![Integrated software and platform Aspect Cross-Departmental Digitization](image)

**Figure G.8: Integrated software and platform Aspect Cross-Departmental Digitization**
Level 3: Vertical and Horizontal Digitization

The smart factory is established and there is complete horizontal and vertical digitization. Connection PLM, ERP, MES is necessary to enable the connectivity between departments and the establishment of the smart factory (Khedher et al., 2011).

Process Aspect

- Smart Factory is established, this means there is machine to machine communication, production lines are no longer controlled individually but are connected with each other. The shop floor is completely autonomous and connected to the enterprise resource systems. Production is controlled from an enterprise level (Wang, Wan, Li & Zhang, 2016).

- Establishment of a digital product twin, this means that a complete virtual representation of a physical product is available (Tao et al., 2018). Based on sensed data from the production facility simulations can be executed to provide a better design of the product. Therefore, product lifecycle management stretches across development and production. Production engineering is now integrated with the product development and automatically shared with the production environment (Kiritsis, 2011).

- A service organization is established and services are accessible across the organization. This means that services are not only depending on the product development but the availability of services can also change product. This requires a certain level of cross departmental service management (Wiesner, Freitag, Westphal & Thoben, 2015).

- The services do not stretch beyond corporate borders therefore product support is still a decentralized activity which is not integrated within the functionalities of the enterprise. The customer is considered an identified customer based on customer data management (Park & Kim, 2003).

Figure G.9: Process Aspect Vertical and Horizontal Digitization
Software Aspect

- Services across the enterprise which means that these services must be designed, maintained and provided. To manage these activities a service lifecycle management (SLM) system can be used. According to Wiesner et al. (2015), it is best to integrate the PLM and SLM, such that the activities influence each other. However, for clarity reasons and to emphasize the importance of service lifecycle management the systems are displayed individually. These systems still operate within enterprise borders.

- PLM stretches across development and production. Furthermore it is now integrated with the ERP and MOMS (Khedher et al., 2011).

Platform Aspect

- The smart factory is established using a special Smart factory information Service Bus. This enterprise service bus enables the integration of both information systems as well as shopfloor hardware and IoT components (Yoon, Um, Suh, Stroud & Yoon, 2019).

- The IoT communication layer serves as the connectivity between the IoT software and the middleware on the higher levels (Porter & Heppelmann, 2014). The high level middleware can be used to integrate the enterprise systems and the IoT communication layer can ensure the connectivity between the ERP system and production data.

- Vertical Integration within the development phase is established by an enterprise service bus and connects on a site level to the production phase. To match product specifications from PDM with production specifications in the MOMS. The integration between development and production can also happen on an enterprise level, using ESB as a middleware between PLM, ERP and MOMS.

- The enterprise systems can be operating on the cloud. As the cloud is not an actual platform it is visualized as an annotation based on the example by (Grefen et al., 2016a). The cloud plays an important role in the analysis of high volume data (Oztemel & Gursec, 2018). In order to optimize manufacturing processes and realize a smart factory is is important to extract value from the data generated by devices, sensors, machines and information systems (Guoping et al., 2017). For example, the IoT data from the shop floor is used to conduct smart analysis for decision support. Furthermore, if data is used across various lifecycles cloud applications often helps to standardize the data formats that supports data integration.

- According to (Carlsson, Hegedüs, Delsing & Varga, 2016), the manufacturing pyramid can be transferred to a local automation cloud architecture. So for example, the MOMS and ERP system...
can be in a local cloud and be connected to another local cloud that holds the lower level systems, such as the SCADA and PLC.

Figure G.11: Platform Aspect Vertical and Horizontal Digitization

Integrated Aspect

Figure G.12: Integrated Aspect Vertical and Horizontal Digitization
Maturity Level 4

Companies digitization stretches beyond corporate borders. The role of the customer and the fast innovation cycle becomes important for improved development and autonomous production.

Process Aspect

- Self-optimizing smart factory based on M2DMM, data is aggregated on the shop floor and basic runtime analytics can be executed locally. Data is aggregated and analyzed on enterprise level to support decision making, which leads to an optimized manufacturing planning and execution (Weber et al., 2017).

- Smart enterprise is established. Supply Chain management, Customers Relation Management, Resource Planning, Product lifecycle management, are no longer individually managed systems when there is Smart Enterprise Control (Conway, 2016). Data is integrated across the product lifecycle which leads to optimized decision making for example in the product phase based on the accurate information that is available.

- The customer is integrated and the relationship between the company and the customer is established (Park & Kim, 2003). Value analysis help to provide better services to the customer, this is also known as a core customer

- Services are no longer internal but are accessible across company borders. This leads to remote product monitoring and supporting the employees during their maintenance tasks using AR.

- Value network control is established once the information of the smart enterprise is accessible for the value chain partners. Enterprise information systems accessible for value chain partners (Leyh, Bley, Schäffer & Forstenhäuser, 2016).

- Supply Chain management can be optimized due to real-time tracking and controlling of products throughout the supply chain (Tjahjono, Esplugues, Ares & Pelaez, 2017). This information leads to optimized enterprise planning

![Figure G.13: Process Aspect Full Digitization](image-url)
Software Aspect

- The collaborative value network is established therefore a supply chain management tool is used to aggregate product information across the supply chain. The role of the SCM is mainly to integrate the information from local information systems of each partner in the value network and make it accessible (Tjahjono et al., 2017).

- Customer service is now an integrated functionality of the enterprise and therefore customer data and relationship value is managed throughout the CRM system (Park & Kim, 2003). It is questionable if a separate CRM system is necessary or this information can also be included in the PLM and SLM system. Nevertheless, good service to the customer is of create importance for the performance of the organization, so a dedicated system might be worthwhile (Yerpude & Singhal, 2018).

- IoT software is added to enable the smart product such that data can be generated from the product in use and its ecosystem. It is important that the services that are required for the smart product as well as the product development are integrated such that the most value can be gathered from the product in use, statement from an expert within Atos.

![Figure G.14: Software Aspect Full Digitization](image)

Platform Aspect

- The ESB is now extended beyond corporate borders across the enterprise. The enterprise systems can be in the cloud, which makes services and applications of the information systems available for suppliers and customers. Again the standardization of the data information systems when using a similar application in the cloud, would allow for improved data integration. The cloud would support real-time tracking of the product across the supply chain.

- The IoT communication layer now also stretches towards the usage/service phase such that there is a connection between the IoT software and the higher level middleware to process and store the gathered data from the product.
APPENDIX G. SMART MANUFACTURING FRAMEWORK

Figure G.15: Platform Aspect Full Digitization

Integrated Aspect

Figure G.16: Integrated software and platform aspect Full Digitization
Maturity Level 5

Optimization of the already established components. Ideal result of the smart manufacturing paradigm. Based on the mapping of the α-model in section 4.3.3.

Main difference is the optimized analytics, based on real time data. Only the process aspect changes the other aspects stay the same as the information systems that are used are similar. The way the data is processed and value is extracted differs and moves towards self-learning as is suggested in the highest level of the M2DMM maturit model (Weber et al., 2017).

Process Aspect

- The value network is optimized due to strong collaborations with partners a single source of truth for product information and new business models and end-to-end solutions.
- All phases of the product lifecycle are connected and optimized based on virtual simulation, real time analysis and accessible product information across the lifecycle.
- The development phase is optimized as design data, production data and customer data are all used to improve the design of the product based on smart analytics and simulations.
- The smart factory can organize itself based on information from the value network, supply chain partners and customers as well as information from the development phase.
- The consumer is connected via personalized accessible services as well as smart connected products that generate information based on the environment and can be controlled remotely.

Figure G.17: Process Aspect Optimized Full Digitization
Software Aspect

![Software Aspect Optimized Full Digitization](image1)

Figure G.18: Software Aspect Optimized Full Digitization

Platform Aspect

![Platform Aspect Optimized Full Digitization](image2)

Figure G.19: Platform Aspect Optimized Full Digitization
APPENDIX G. SMART MANUFACTURING FRAMEWORK

Integrated Aspect

Figure G.20: Integrated Software and Platform Aspect Optimized Full Digitization
Appendix H

Implementation

The elements that are used for the implementation approach are presented in the first section of the appendix. Thereafter, the elaborated results from the gap analysis and roadmap are discussed. A detailed overview of the implementation approach is presented in the first section of this appendix. Thereafter, the results of the implementation are discussed.

Implementation approach

Detailed questionnaire

The second method is a detailed questionnaire based on the four aspects of smart manufacturing mentioned in Section 4.2. The approach of the interview is semi-structured. The questions that serve as a guideline for the interview are shown below. The semi-structured approach leaves some flexibility during the interview, to ignore questions that are irrelevant and ask follow-up questions where necessary. Based on the answers the current maturity level of the company can be determined.

Vertical Integration

Which Industry 4.0 activities are currently performed?

How is your company organized?

- Is there a department for product development?
- How many production facilities are there?

On which hierarchy level does production planning occur?

- Is there a flexible planning across the various production facilities?

Which systems are used to support the product development?

How is information shared within the departments?

- Is information siloed?
- Is there a common database?

Do you use information systems to support business planning?

What is the level of automation within the factory?
Horizontal Integration
Which areas of your company are supported by information systems?
Is there integration between information systems?
Is information automatically transferred among departments within the company?
How is data shared with supply chain partners?
  • Is there one connecting source via a platform?
  • Is data always available for partners?
Is there automatic production control based the resource planning or customer orders?

End-to-end Integration
Can products be tracked across the lifecycle?
How is information from the product during production used to develop the product?
How is information from the product during the usage period used to develop the product?
How is the support of the product arranged during the usage period?
Are products designed and build as smart products? Which functionalities do they have?

Technology support
Which platforms are currently supporting the information systems and applications?
Are there cloud based solutions?
Which Internet of Things applications are used?
Are there services available within the company?
Are these services accessible enterprise-wide?
Which big data applications are used?

Ranking of smart manufacturing key capabilities
Table H.1: Smart manufacturing functionalities and supported key capabilities, taken from Lu, Frechette and Morris (2016).

<table>
<thead>
<tr>
<th>Functionality/System</th>
<th>Key Capability support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Lifecycle Management</td>
<td>Quality, Agility, Sustainability</td>
</tr>
<tr>
<td>Supply Chain Management</td>
<td>Agility, Quality, Productivity</td>
</tr>
<tr>
<td>Design for Supply Chain Management</td>
<td>Quality and Agility</td>
</tr>
<tr>
<td>Continuous process improvement</td>
<td>Quality, Sustainability, Productivity</td>
</tr>
<tr>
<td>Continuous Commissioning</td>
<td>Productivity, Agility, Sustainability and Quality</td>
</tr>
<tr>
<td>Design for Manufacturing and Assembly</td>
<td>Productivity and Agility</td>
</tr>
<tr>
<td>Flexible Manufacturing System</td>
<td>Agility</td>
</tr>
<tr>
<td>Manufacturing Pyramid</td>
<td>Quality, Agility, Productivity and Sustainability</td>
</tr>
</tbody>
</table>
Implementation Results

The detailed results of the implementation for both the gap analysis and the roadmap are given here.

Case-study 1

Gap Analysis

First the gap between maturity stage 1 and 2 must be bridged. This is only a software system implementation, namely the MOMS. The BPMS is to automate the manufacturing activities, which is in this case only relevant for automatic messages to the shop floor employees and not for machines. Furthermore, the interviewee mentioned that the BPMS should stretch across the entire enterprise such that all processes are defined accurately.

The gap between 2 and 3 exists for both the platform and software aspect and thus implicitly also on the process aspect. Platforms to support both the vertical integration of the development and production phase, i.e. ESB, SIBUS and IoT Communication Layer, must be implemented. To support the horizontal integration the ESB on enterprise level is established. This leads to integration of the ERP, PLM, SLM and MOMS. The SLM system is a new system that must be implemented to ensure that the organization is service-dominant. Furthermore, both the PLM and SLM now stretch beyond their department and provide more end-to-end integration. Data analysis should be improved to establish the digital product twin and smart factory.

The gap towards level 4 applies again to all the aspects. The company is now engaged in a value network and thus two new systems are necessary, the SCM and CRM to connect to suppliers and customers. The SCM, CRM, PLM and SLM should all be available on a network level and might be in the cloud. The should be integrated by an ESB that also stretches towards the ERP system.

Roadmap

Activity 1

Make a choice for a information system that support the production facility. Instead of first implementing individual systems for the various functionalities, as is suggested for stage 1, it is recommendable to directly implement a MOMS. The MOMS covers all the functionalities, Quality, Maintenance, Operations managements. Note Inventory management is already covered by the ERP system. When implementing the MOMS directly the first stage is omitted and the step towards the second maturity stage is made directly.

MES systems of various vendors are available that provide the above mentioned functionalities. For this reason a MES system including these functionalities would be sufficient to fulfill the requirements of stage 2.

Activity 2

Directly after the implementation of the MES follows the second step. It is important to integrate development and production. This is possible by generating the work instruction in the PLM system, based on the product data that is available, and provide this to the MOMS system. The functions and possibilities of the production then match directly with the design of the product. The PLM system is integrated with the MOMS and ERP system via an ESB. This fulfills a level 3 requirement

Activity 3

At stage 3 the enterprise should be service-oriented. Therefore, a SLM should be implemented in the enterprise. The company must determine which services are provided within the organization and make sure that they are accessible enterprise-wide. The management and improvement of services can be based on product information from the PLM system. This makes it a follow-up activity from product development. It is better to integrate the SLM and PLM. Once changes occur in the process of product development or production, the direct integration of the two systems allows for an immediate improvement of the services. The processes should also be modelled in such a way that they are service-oriented.

Activity 4

Improved data analytics to establish the product twin and smart factory. The results from the data
analysis can improve the quality and flexibility within the enterprise. Using cloud applications can accelerate the use of data analytics as standard data formats are used and many cloud applications have standard data analytics functionalities.

**Activity 5**

The first step towards stage 4 maturity is the accessibility of the information in the PLM system towards the partners in the value chain. The PLM system must be transferred to a network level and preferably be a cloud application, such that it can connect with other systems from for example suppliers. It is important to ensure a high IT security such that data cannot be changed without permission. The integrated SLM system moves together with the PLM system such that the services are also available across enterprise borders.

**Activity 6**

SCM system implementation leads to integration between your own systems and the various systems of the suppliers. The SCM should at least be connected to the ERP and PLM system to ensure that the information is up to data and thus correct. Due to the frequent updated data from within and outside the enterprise, scheduling of production and logistics can be done more accurate.

**Activity 7**

Connecting the customer using an integrated CRM system with a friendly user interface. This makes it easier to fulfill the customers demands. A sales configurator can be part of this customer system. As the system is integrated with the enterprise systems PLM and ERP, the requests of the customer can be verified based on information that is available in those systems. For example an accurate production planning can be made, based on the available resources and product information, such that the customer knows exactly when the product arrives.

**Case-study 2**

**Gap Analysis**

The main gap that must be bridged is the one between maturity stage 3 and stage 4. Although, some of the elements are still missing to fully support stage 3 maturity, namely the dedicated SLM. Once that is established the company can move from stage 3 to 4. The gap between these stages applies on the platform, software and process aspect. The company should engage in a collaborative value network and thus an integrated CRM system must be implemented. Furthermore, multiple systems must be made accessible on a network level, such as the PLM, SLM and SCM. These systems must all be integrated by an ESB and could benefit when they are in the cloud, because of standardization. Another important gap is the development of smart products. The products contain IoT software, such that the data in use can be processed in real-time.

**Roadmap**

**Activity 1**

Implementation of digital service lifecycle management. To fully establish level 3 maturity it is necessary to provide services that are available within the enterprise. These services can for example hold, activity based production process steps or augmented based production. Therefore, it must be determined which service are provided within the organization. Managing and improving the services can follow from the product information in the PLM system and would therefore be a follow-up of the product development. A better approach is to integrate the Service Lifecycle Management and the PLM system. As soon as changes occur in the production process or product development, this can lead to changes in services. The SLM and PLM should be integrated and available via cloud, so it is accessible within the entire enterprise.

**Activity 2**

The information systems should be cloud-based applications, which makes data analysis easier and more important to ensure quality and flexibility. It is important to perform data analytics for both product development and production systems. These analysis can be simulations, based on product information to simulate its performance, or analysis based on deviation measured in the MOMS system. This can lead to improvements in product design or the way of production. Value is created based on the digital
product and production twin, ensuring all data is available digitally to perform relevant analysis.

**Activity 3**

The PLM system and ERP system should be available on a global, enterprise-wide level, and be standardized. These systems should be integrated to the local available enterprise systems, such as PDM, MES, Warehouse Management and CRM systems. Data migration is of great importance here, as the local systems might differ and therefore the data structure and information might differ. Establishing a standard base in the PLM system and ERP can secure quality and productivity around the globe, as the same, usable information is available to every site.

**Activity 4**

The first step towards a level 4 maturity is the IoT program for products in use. As a start is already made in this direction it makes sense to pursue this even further. It is important that the services that are provided based on the new opportunities are also adapted in the SLM. Furthermore, the implementation of IoT for products at the clients, also changes the development of the product. It is important that during the product design and development the IoT requirements are integrated. The data that is gathered from the product in use, serves as an important source for data analysis to establish predictive maintenance, but also improvements of the product.

**Activity 5**

Secondly the accessibility of the PLM system for the partners in the value chain. The PLM system should therefore be available on a network level and accessible via cloud. To share the data automatically between suppliers, bi-directional, the IT security is of high Importance, such that information cannot be changed in the systems unauthorized. The integrated SLM system also moves to a network level, such that the services are available across the value chain.

**Activity 6**

Implementing a global supply chain management system. This system should be integrated with the PLM and ERP system, such that data is up to date and the correct information is available for supply chain partners. The SCM acts as an integration method between the various systems of suppliers and mostly uses data from the ERP system. Based on the frequent updates of data and also RFID availability for product tracking, data is more accurate, which improves production planning and product delivery.

**Activity 7**

Additional link to the customer to establish a fully connected customer. The integrated CRM system, with a user friendly interface, makes it easier to fulfill the customers desires. Sales configurators can be part of the customer system and integrated with the enterprise systems to determine the feasibility and accurate processing times based on real-time data. Furthermore, the order can be processed automatically, as product information is available and inventory is up to date the orders can be placed at suppliers using the SCM system. The automation also ensures more agility and quality, without harming the productivity and leading to longer lead times.

This high-level roadmap is prepared based on the models shown in this report. The gap that exists between the two stages must be bridged. Concrete systems that fit the situation best are not part of this analysis, as vendor specific knowledge is not available. Therefore, it remains at high-level conceptual steps and activities. The gap is split into smaller pieces to make the approach more applicable and feasible. The approach can be completed by providing structures and recommendations for vendor-specific systems, data-migration, data analytic methods and system integration.
Appendix I

Evaluation

The smart manufacturing framework is evaluated on relevance using the five criteria defined by (Shrivastava, 1987). The detailed evaluation approach is provided below.

**Meaningfulness**

- How does this framework contribute to your understanding of smart manufacturing?
- Is the framework enhancing issues that are relevant?
- Which of the aspects of the framework are most relevant?
- Is the framework approach understandable?

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**Goal relevance**

- Does the framework provide insights how the current situation and future visions are aligned?
- Does the framework help to guide towards future visions?
- Are the performance metrics aligned with possible business goals for your company?

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</table>

**Operational Validity**

- Is it possible to put the results of the framework into practice?
- Are the activities concrete?
- Are the implications of the activities clear?
APPENDIX I. EVALUATION

Concreteness 1 O O O O O 5
Clarity 1 O O O O O 5
Operational 1 O O O O O 5
Conceptual 1 O O O O O 5

**Innovativeness**

- Does the framework address new solutions?
- Are new insights put into practical problems?
- Is the approach of the framework innovative?

Commonsense solutions 1 O O O O O 5
Innovativeness 1 O O O O O 5
Solution Relevance 1 O O O O O 5

**Cost of Implementation**

- Are the activities feasible?
- Is it possible to reach the next maturity level within a certain time frame?

Feasibility 1 O O O O 5