CHALMERS
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The Future of E/E Architectures in Connected Environments

A Study to Guide Design and Development

Master’s thesis in Product Development

MARIUS JOHR

Department of Industrial and Materials Science
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Examiner: Professor Ola Isaksson, Department of Industrial and Material Science

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Department of Industrial and Material Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

In collaboration with:
3DSE Management Consultants GmbH
Seidlstraße 18a
80335 Munich
Germany

Gothenburg, Sweden 2019

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Abstract

The internet of things is assessed as one of the most disruptive technological advances that are predicted to transform life, business and the global economy. Moreover, almost every industry is impacted from this technological disruption due to the great versatileness of connected functionalities. Thereby the increasing connectivity impacts especially electric and electronic (E/E) architectures, since they can be seen as the main innovation drivers in modern products. However, companies moving towards more connected products encounter different challenges in terms of design and development of connected products, which calls for a shift in the way E/E architectures are designed and developed in connected environments.

This thesis aimed to examine which characteristics futureproof designs of connected E/E architectures feature and how such architectures are to be developed from a strategical, processual and organizational perspective. Further it was examined if design and development approaches differ for the respective applications and reasons for these differences were investigated. This aim was approached by a three stepped process. First a literature study was conducted theoretically analysing the impact of increasing connectivity on the general structure of E/E architectures. Second, an empirical study in form of expert interviews was conducted trying to understand how R&D organizations across different industries design and develop connected E/E architectures. Lastly, the insights gained from the interviews were consolidated into a conceptual decision model guiding companies in design and development of connected E/E architectures.

The literature study indicated the emergence of a new functional layer in connected E/E architectures potentially adding additional complexity to the already existing one. Based on the empirical industry study it could be concluded that there certainly is no one-size-fits-all approach for designing and developing future connected E/E architectures. Insights regarding different drivers, design and development approaches followed by the interviewed companies were gained. The results of the interviews were consolidated by defining 37 criteria describing drivers, architectural design and development. The criteria were linked to each other by conducting an interdependence analysis. Finally, dependency profiles were formulated summarizing identified findings and enabling to decide upon suitable design and development characteristics.

Keywords: E/E Architecture, Electrics & Electronics, Product Architecture, System Architecture, Systems Engineering, Product Development, Connectivity, Internet of Things

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A. Table of Content

B. Acronyms

B2B	Business-to-Business
B2C	Business-to-Consumer
CE	Consumer Electronics
DSM	Design Structure Matrix
E/E	Electrics & Electronics
ECU	Electronic Control Unit
IoE	Internet of Everything
IoT	Internet of Things
OEM	Original Equipment Manufacturer
PA	Product Architecture
R&D	Research & Development

1. Introduction

This chapter aims to give an introduction to the research conducted in the course of this thesis. This is conducted four steps. First, an overview is given regarding the specific research field by outlining the problem to be investigated in this thesis and the novelty of this specific research. Second, the specific aim of the thesis is defined, followed by breaking this aim down into three objectives to be fulfilled. Lastly, the scope of this research is mapped out by defining the underlying delimitations of the research.

1.1. Background

When talking about connectivity or connected product systems in many cases the term Internet of Things (IoT) is used. According to Manyika et al. (2013) the IoT is assessed as one of the most disruptive technological advances that are predicted to transform life, business and the global economy. They further predict it to have a direct economic impact of 2.7 to 6.2 trillion US$ per year by the year of 2025.
Di Martino et al. (2018) define the term IoT as one part of the so called internet of everything (IoE), which enables connecting cyber, physical and biological worlds with each other by utilizing smart sensors and devices to collect and share data between these entities. He states that this in most cases refers to consumer-level devices However, under the same umbrella of IoE Di Martino et al. (2018) talk about the Industrial Internet (II) also referred to as Industrial Internet of Things, which in contrast to the just mentioned IoT tends to be applied for more industrially focusing applications ranging from the aerospace sector to healthcare applications. Jankowski et al. (2014) also put emphasize on the fact that the term IoT has an enormous breadth in the range of products it is referring to. In what they call the IoT landscape product applications range in a similar way from consumer-focused wearables to applications in the area of healthcare and transportation. Even the most recent studies show that there cannot be pointed a single key application and IoT rather impacts almost all possible industries (Mauerer, 2019). Comparing the different definitions of IoT and the products they are referring to might not deliver a clear definition, but it clearly shows how broad the fields of applications is.

Further, the great versatility of connectivity is not only given the fact that it is applicable in various kind of industries, but also due to the fact that connectivity can be applied in significantly different levels of sophistication. An illustrative way of categorizing these various sophistication levels is outlined by Porter and Heppelmann (2014). They are characterizing the potential applications of connected products into the four categories “monitoring”, “control”, “optimization” and “autonomy”, where monitoring represents the most basic functionalities possible. Full system autonomy on the other hand is referred to as the most sophisticated application possible on this range. Combining both these perspectives on versatility of connectivity it can be assumed that there is actually no industry in the future, which is not to some extent affected by the impact of increasing connectivity.

However, developing connected products is not necessarily straightforward especially for companies, which did not touch upon developing complex and connected products before. In the light of this technological disruption, companies encounter various barriers and challenges when moving their product portfolio from standalone products to connected, data sharing product systems. Schröder (2016) points out that the lack of standards and data security issues are among the biggest challenges, when companies moving towards a more connected product portfolio. This is especially the case for small and medium-sized enterprises. Likewise Ganguli and Friedman (2017) conducted a study where “security concerns”, “implementation/integration complexity” and “Technology is immature” were outlined as three of the top barriers associated with activities in the field of IoT.

Thus, in order to overcome these barriers and maximize the benefit associated with developing more connected products it seems necessary to rethink the way future products are designed and developed. In the field of research and development (R&D) a way of dealing with product development issues such as product change and complexity management is to consider the product architecture. Ulrich and Eppinger (2012) define product architecture as "the assignment of the functional elements of a product to the physical building blocks of the product".

However, the newly emerging requirements coming along with increasing connectivity affect certain parts of the product architecture more than others. Broy et al. (2009) break down the architecture of complex products such as modern cars or aircrafts into mechanics, electrics and electronics and software. Thereby, especially the combination of electrics and electronics and the associated software referred to as electric and electronic (E/E) architecture is one of the most important innovation drivers. In modern cars up to 90 % of the innovation is based on improvements in this product area (Robert Bosch GmbH, 2014). This means that innovation associated with increasing connectivity will most likely be enabled by innovation in this system layer either. Navale et al. (2015) examined the evolution of automotive E/E architectures and conclude with regards to future upcoming challenges:

> “*Today's E/E Architectures have been capable of handling the requirements of the past, but they may not be as effective for future requirements. There are several bottlenecks for implementing tomorrow's functionalities into today's E/E Architecture patterns*”

They further outline “external communication” and “extensibility & flexibility” as two architectural bottlenecks, which are directly linked to field of IoT.

This motivates the question of how to design future E/E architectures in more complex and interconnected systems. Moreover, besides enlightening the field of future connected E/E architectures from a design perspective there is the need for answering the question of how R&D organizations address these challenges from a strategical, processual and organizational perspective. Answering these questions above and deriving generic recommendations from them can help companies in developing future proof E/E architectures. Products consisting out of such future proof architectures are capable to utilize the numerous potential benefits resulting from the IoT especially with regards to optimization and autonomy.

Nevertheless, while answering these questions it should be kept in mind that connectivity does on the one hand impact several different industries and on the other hand can be applied in significantly different sophistication levels. The significantly different uses cases resulting from these different application areas and their respective requirements have to be considered in order to provide true value for each individual company targeting to move towards more connected products, rather than assuming a one-size-fits-all approach provides appropriate solutions for this problem.

1.2. Aim

In order to guide companies in the future moving towards more connected products and facilitate their decision making in terms of selecting an appropriate design and development approach, the aim of this thesis is as follows:

> *Examine which characteristics futureproof designs of connected E/E architectures feature and how such architectures are to be developed from a strategical, processual and organizational perspective. Further, examine if design and development approaches differ for the respective applications and find underlying reasons.*

The information gained by this conducted research intent to facilitate decision making especially on higher management or system architect level, rather than providing detailed technical specifications applicable for detailed design processes.

1.3. Objectives

In order to work towards this aim in a structured manner three objectives are defined guiding the course of this research and building successively on each other:

Objective 1: *Build understanding how E/E architectures are structured across industries and explore how this structure is affected by increasing connectivity.*

Objective 2: *Explore how R&D organizations across different industries design and develop connected E/E architectures and understand why certain design and development approaches are chosen*

Objective 3: *Consolidate the findings regarding design and development of connected E/E architectures into a conceptual decision model to guide design and development activities of companies moving towards more connected products.*

These three defined objectives build successively on each other meaning further that each objective cannot be fulfilled without fulfilling the respectively preceding one. In how far the three objectives depend on each other is outlined in further detail in Chapter 2.

1.4. Delimitations

Since this research is conducted in a limited time frame a set of delimitations have to be made in order to keep the process of achieving the objectives in a manageable scope and clearly limiting the boundaries of the research to be conducted.

The first delimitation to be made concerns the nature of this research as a rather explorative approach of understanding the future of E/E architectures with regards to complex systems and connectivity. This thesis is neither part of a comprehensive scientific research program nor is based on successive industrial development activities. Thus, it has to provide both a fundamental understanding of the topic and a novel outcome accordingly to aim and the corresponding objectives. Thus, this report and especially the derived model to be developed according to objective 3 does not claim to be exhaustive. Rather the aim is to build a fundamental framework capable for scaling and further improvement once more knowledge is gained and technology is progressing.

Secondly, this thesis is balancing in a research field between rather technical descriptions and purely strategic findings. This however means at the same time that both these areas cannot be covered in full detail. This indicates especially with regards to the design recommendations, that the architectural descriptions made and utilized throughout the thesis are on a relatively high level of abstraction and do not go into technical detail. Meaning, the conclusions made in this thesis will not be suitable to guide software developers and electrical engineers in designing specific components. The results of this thesis should rather facilitate the general decision-making process on a R&D management or E/E architect level.

2. Research Approach and Methodology

The following chapter aims to describe the overall research approach applied for achieving the aim of the thesis. The approach how the research is conducted aligns with the three formulated research objectives, whose results successively build on each other. The study approach hereby refers to the general direction to be followed working towards the respective objectives, whereas the methodology describes the different methodological steps following this approach. Figure 1 gives an overview of the general study approach. It shows how each objective is approached respectively and how the respective objectives build on each other.

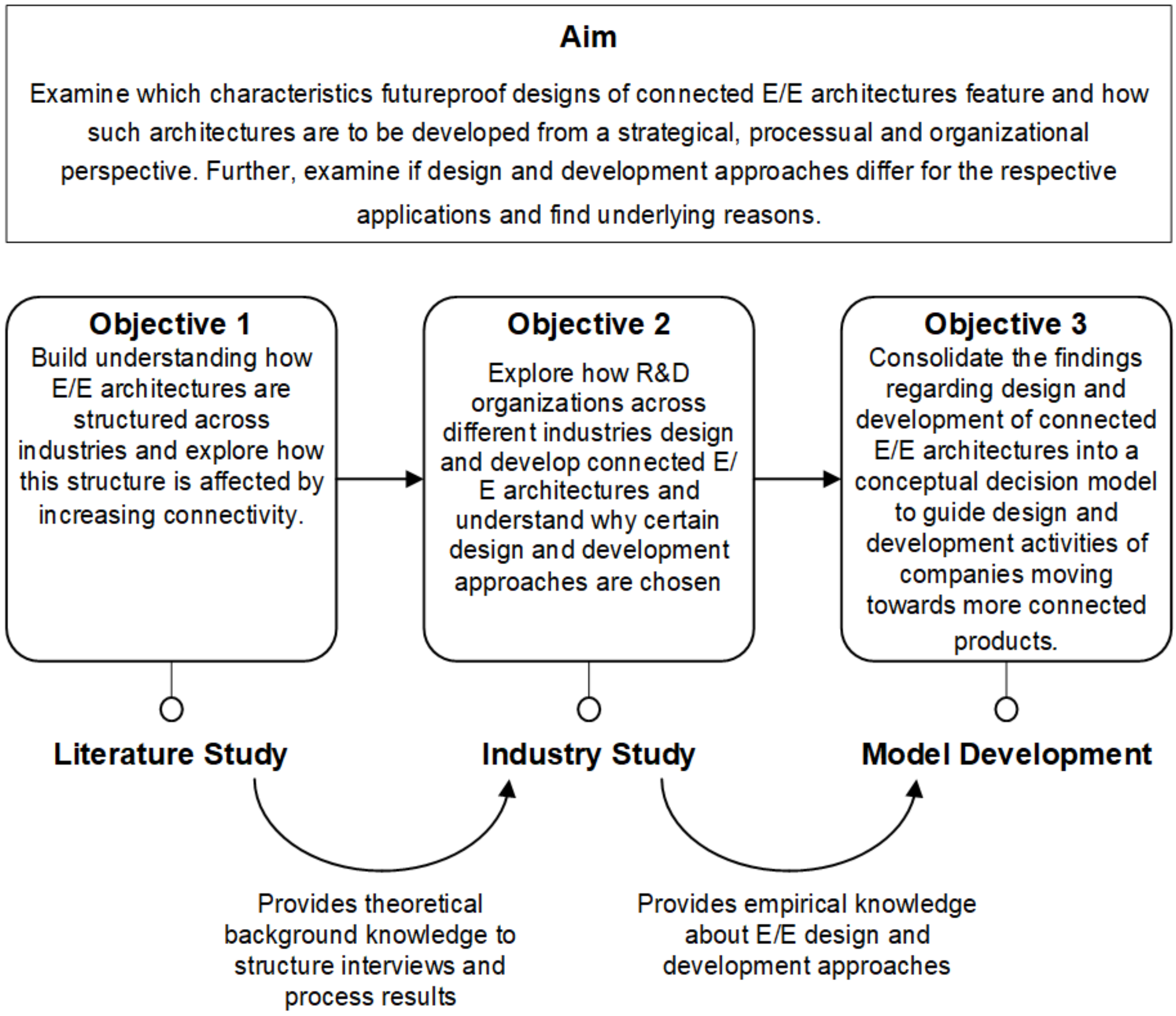

Figure 1: Study approach overview

Before approaching Objective 1 the general term of product architecture is introduced by referring to relevant literature. Objective 1, which aims to build fundamental understanding of E/E architectures and the impacts of connectivity on the general structure, is approached by a comprehensive literature review. After building this theoretical basis objective 2 is approached by an empirical study in form of expert interviews, in order to understand how E/E architectures are designed and developed across different industries. Lastly, Objective 3 is approached by analyzing the empirical data gained from the expert interviews aiming to derive a generic design and development model for connected E/E architectures out of it.

2.1. Product Architecture Foundations

Before start working towards the defined research objectives the term of product architecture along with its implications for product development processes is briefly outlined in order to understand why E/E architectures have to be considered anyway. This is achieved by utilizing established literature from the field of product development and systems engineering. Lastly, the necessity of considering product architectures in the field of increasing connectivity is outlined.

2.2. Literature Study

Objective 1 is approached by conducting a comprehensive literature study aiming towards investigating the overall structure of E/E architectures and the impact of increasing connectivity on this structure.

Since architectural consideration concerning E/E systems are identified as key levers to overcome barriers associated with moving towards more connected products the literature study is dedicated to the structure of E/E components. Due to the fact that the term E/E architecture is especially used within the automotive and aircraft industry most of the theoretical information such as definitions and architectural descriptions is discussed, from these areas perspective. However, products in these areas belong to the most complex ones. Thus, this information is analyzed with respect to the possibility to derive a generic E/E architecture structure out of it. Out of the literature analysis a generic architectural description is developed suitable to describe E/E architectures across different industries.

In the next phase, it is examined how E/E architectures are impacted by increasing connectivity. This is done by first defining major implications coming along with increasing connectivity and digitalization. Afterwards, it is analyzed how the generic E/E architecture mapped out before is impacted by these implications. Therefore, among others functional architectures of consumer electronics are analyzed and based on their architecture it is assumed how the general structure of E/E architecture will change.

Lastly, conclusions are drawn regarding what challenges will result from the architectural changes triggered by increasing connectivity, by comparing challenges from the past with those emerging in the future. Further, the relevance of the developed reference architecture is discussed.

2.3. Industry Study

One major issue resulting from the rather new technological impact of increasing connectivity is, that there are relatively few evidences how the different architectural layers outlined in the end of the literature study are designed and developed across industry. Thus, in order to achieve objective 2 and explore how E/E architectures are to be designed and developed, a set of expert interviews with representatives of various industrial contacts is conducted.

In order to provide an overview of various industries 10 interviews with experts working within the field of E/E system development were conducted. Since the inisghts to be developed in course of this thesis aim to act as a decision tool on a relatively high management level it was necessary to talk to people having a holistic view on the development organization and their processes either. In order to establish contact with such superordinate roles in large R&D organizations the customer portfolio of 3DSE Management Consultants GmbH was utilized.

The interviews were conducted in a semi-structured manner in order to ensure comparability on the one hand, but on the other hand leave the necessary space for the interviewees to bring up what is important from their perspective. The questions asked in the interviews aim to give insights into three different areas. The first part aims to map out the adaption level of connected products and along with that identify drivers and hurdles for initiating development activities. The second part deals with the question how the respective E/E architectures will change in the future in terms of design. In order to compare the design of the architectures applied across industry the reference architecture developed in course of the literature study is utilized. The last part of the interviews focusses on the changes from a development point of view. Hereby, it is of interest if established development procedures will also be suitable to successfully develop future-proof connected E/E architectures.

In order to ensure comparability between the different expert interviews an interview guideline is utilized, which is shown in Appendix 1. The structure of the interview is furthermore set up in a modular way to accommodate to the respective time availability of the different interviewees and enable scaling time duration of the interview from 30 – 60 minutes.

After presenting the results of the industry study it is discussed in how far the different architectural layers mapped out in the E/E reference architecture differ and what implications this has on future product development. Furthermore, the gained data is analyzed in order to understand how the differences in architectural design and development come about. Therefore, it is first tried to derive E/E architecture archetypes from the results featuring the most prominent architectural characteristics examined throughout the interviews. Afterwards, more generic hypotheses are developed aiming to make the results processible in the subsequent model development process.

2.4. Model Development

Objective 3 successively builds on the empirical and analytical results gained out of the conduced industry study. It aims to compile the findings into a generic decision model guiding design and development processes of E/E architectures in connected environments. Thereby the raw data gained form the interviews is made accessible for potential users.

In order to develop an appropriate decision model, the clear purpose of the model and a set of requirements have to be mapped out. The requirements applied in this case especially refer to usability, visualization, quantifiability and scalability of the model. Next, based on the defined purpose and requirements a suitable model type is chosen, potentially capable to provide value in the research context. In this step ideally, some form of consolidation is performed boiling down the great amount of data into certain key factors applied in the model. However, it must be critically reflected upon the data set with regards to how much consolidation is appropriate under the given circumstances. After selecting a satisfactory model type, the model can be formulated. Therefore, the data set gained throughout the empirical study is utilized to outline a set of inputs and outputs, capable to describe E/E architecture design and development. In the next step it is defined how the inputs and outputs correlate with each other, what determines the logics of the model. Due to the fact that a rather comprehensive model type is chosen including several inputs and outputs this interdependence analysis is performed by employing a design structure matrix (DSM). Based on this interdependence analysis the different artefacts of the model are formulated.

Further, the formulated model is applied in an idealized case throughout the development process in order to evaluate certain aspects of the model and find areas of improvement. These insights are utilized to perform a model refinement iteration aiming to improve the first draft of the model. Aspects evaluated in course of this model application are logics, usability, value of recommendations. This application is performed with a representative from industry.

3. Product Architecture Foundations

The following section aims to give a brief overview about the theoretical foundations of product architecture in general and why product architectures have to be considered. Therefore first, the theoretical foundations are mapped out by defining the term product architecture which is followed by the most important characteristics. Afterwards, implications of product architectures in the field of product development are outlined. Finally, the chapter is closed by outlining the necessity of considering product architectures in the field of increasing connectivity.

3.1. Product Architecture Definition

Even though the term product architecture (PA) is almost of universal usage, there is no single definition. Rather, every domain defines architecture respectively and even in one specific domain experts do not agree upon one definition. Ulrich (1995) was one of the first authors utilized the term of product architecture by outlining general characteristics and implications on the development process. His perspective on the term architecture is specially associated with physical products and reads:

> *"Product architecture is the scheme by which the function of a product is allocated to physical components"* (Ulrich, 1995)

Maier and Rechtin (2002), Crawley et al. (2004) and Haberfellner et al. (2015) on the other hand consider architecture more from a system's perspective, which makes their definition even more generic:

> *"The structure (in terms of components, connections, and constraints) of a product, process or element"* (Maier & Rechtin, 2002)

A dedicated IEEE working group clearly outlined that architecture should be though as a high abstract concept, rather than a "structure" because this would only refer to its application on physical products (IEEE, 2007). Furthermore, they stress on the fact that architecture does not only refer to the system itself but also to the system's environment, which has to be considered in an architectural description. Thus, it can be seen the different definitions of the term architecture are highly depended on the level of abstraction applied. However, Maier and Rechtin (2002) state that it is not of highest importance to have one common definition, rather it is of importance to understand what the architecture is about and what implications it has for industrial product development processes.

But the level of abstraction does not only vary in terms of the element the architectural description is referring to. The way how abstract the architectural description is expressed can vary to some extent as well. In literature it is often stated that architecture, no matter if referring to a single physical product or an entire system and its environment, can be thought from a functional or physical perspective (Ulrich & Eppinger, 2012) in its two abstraction extremes. The functional architecture which is sometimes also referred to as function structure (Göpfert, 2009) is established by hierarchically decomposing the system's main function into several individual but still interacting operations and transformations. This aims to reduce the complexity of the development task and outline the relationship of the different sub-tasks to each other (Göpfert, 2009; Ulrich & Eppinger, 2012). The physical or technical architecture on the other hand describe how the defined sub-functions of the system are implemented in the product by parts, components and subassemblies (Göpfert, 2009; Ulrich & Eppinger, 2012).

Ulrich (1995) states that the most important topological characteristic of a product architecture concerns its modularity. Depending on the level of modularity an architecture can be modular or integral. Thereby it is important to mention that architectures can rarely be characterized as strictly modular or integral. It rather is a continuum between these two bookends and must be assessed relatively to a comparative product (Ulrich & Eppinger, 2012). A one-to-one mapping of functions to physical components represents a modular architecture (Ulrich, 1995). In addition, the interactions between the individual components are well defined by only a few set of interfaces (Ulrich & Eppinger, 2012). Sometimes these clearly defined interfaces are even still visible in the usage phase of the product (Göpfert, 2009). An integral architecture on the other hand exhibits a significantly more complex mapping between these two architectural perspectives. Here several different functions are mapped on a single architectural chunk of the product or on the other hand one function is realized by spreading it across several different chunks. Thus, the way how the respective chunks interact with each other is not as properly defined as it is the case in modular (Ulrich & Eppinger, 2012). Göpfert (2009) further states that the term modularity can refer to both the functional or the physical architecture. Whereas Ulrich and Eppinger (2012) refer mainly to modularity as a general term, do Baldwin and Clark (2000) distinguish between three different types of modularity: modularity in-design, modularity in-production and modularity in-use, which respectively refer to different phases of a product's life time.

3.2. Product Architecture Implications

Ulrich (1995) argued that architectural processes can be considered as key drivers in affecting a manufacturing firms performance in several different aspects. The chosen product architecture further has impact on parts of the enterprise concerning manufacturing capabilities or even marketing strategy (Ulrich & Eppinger, 2012). PA has impact on almost the entire life cycle of a product. This can range from developing the first architectural concept to the very end of the usage phase of the product. As such PA is associated with assessing a products feasibility on the one hand and ensuring its integrity throughout operational and evolutionary phases (IEEE, 2000). Ulrich and Eppinger (2012) summarize that PA affects among others the following issues inherent in product development enterprises: product change, product variety, component standardization, product development management and product performance.

According to Ulrich (1995) the applied PA has significant effect on the way a product can be changed. Here he distinguishes between different kind of changes, but also states that PA concerns both these types of changes. First, changes to certain artefacts of a product during the actual life time or usage phase of the product by for example replacement of parts within maintenance activities on the one hand. Second, changes to the product line or model performed in the design process between different derivatives of a product on the other hand. By the way physical building blocks of a product are arranged in the PA and moreover connected to each other, it is determined what other components or artefacts are affected by this change (Ulrich & Eppinger, 2012).

According to Maier and Rechtin (2002) systems architecting can be seen as a means of dealing with high complexity. In product development organizations such high complexities can result from having a high product variety. Companies manufacturing a large variety of different components and thereby utilizing a large variety of different tasks have to deal with what Baldwin and Clark (2000) call it a “complexity catastrophe”. By building products around a modular architecture such complexity catastrophes can be avoided. In this case a set of standard chunks is utilized, which are combined in defined manner (Ulrich, 1995).

Moreover, Ulrich (1995) mentions the significance of PA for effective product development management. The way a product is divided into smaller subunits can to some extent be mapped to the development organization as well. Thereby complex development projects are broken down into smaller better manageable units (Maier & Rechtin, 2002) and can be performed in parallel (Ulrich, 1995). However, due to its architectural interdependency to other components within the product architecture it is important to consider the interaction of the assigned components with each other. In this case a modular architecture is more beneficial since it allows for assigning development tasks to smaller sub-groups without requiring close collaboration and intensive communication between the different development teams. This architecture-based assignment of different tasks can be performed both within an organization or beyond an organization's boundary by involving suppliers and sub-suppliers. Especially development organization heavily depending on external suppliers can thus benefit form modular product architectures (Ulrich & Eppinger, 2012).

Lastly, Ulrich and Eppinger (2012) state that PA significantly impacts the overall product's function such as in terms of weight, volume and cost. Crawley et al. (2004) further outline that PA has a considerable impact on how well a product is performing its intended main function. They refer to such properties influencing a product's performance as "ilities". A collection of these ilities according to Crawley et al. (2004) is shown in Table 1.

Table 1: Exemplifying list of ilities describing a product's performance affected by the chosen product architecture by Crawley et al. (2004)

Ilities	Definition according to Crawley et al. (2004)
Robustness	"The demonstrated or promised ability of a system to perform under a variety of circumstances, including the ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent"
Adaptability	"The ability of a system to change internally to fit changes in its environment"
Flexibility	"The property of a system that is capable of undergoing classes of changes with relative ease"
Safety	"The property of being free from accidents or unacceptable losses"
Scalability	"The ability of a system to maintain its performance and function, and retain all its desired properties when its scale is increased greatly, without causing a corresponding increase in the system's complexity"

3.3. Research Relevance Product Architecture

Besides briefly introducing the term product architecture and referring to the different viewpoints on architecture, this chapter outlined the importance of architectural considerations in the area of R&D. The fields in the area of product development product architecture has a high impact on such as outlined by Ulrich and Eppinger (2012) and Crawley et al. (2004) directly touch upon the research field examined in course of this thesis. In chapter 1.1 it was outlined that technological immaturity, complexity of implementation and data security/privacy issues are among the biggest challenges associated with moving towards a more connected product portfolio. And indeed, it is the case that all these three barriers can be somehow related to architectural considerations on either product or system level according to the implications mentioned by Ulrich and Eppinger (2012) and Crawley et al. (2004). When further referring back to the fact that especially E/E components will be heavily affected by these technological innovations, it can be concluded that investigations concerning design and development of future E/E architectures facilitate companies in overcoming the mentioned barriers.

Moreover, approaching these challenges from an architectural point of view is beneficial due to the fact that in digital and connected products system component from very different fields such as electrical engineering and information technology come together. Increasing connectivity and digitalization will blur the line between these system components. The same is the case for the differentiation between a product and its environment. Architectural considerations have the potential of dealing with this issue in a holistic manner by making usage of the different architectural points of view and definitions used in different fields.

4. Literature Study

By conducting a comprehensive literature study objective 1 of the thesis is aimed to be achieved, which is defined as:

> ***Objective 1:*** *Build understanding how E/E architectures are structured across industries and explore how this structure is affected by increasing connectivity.*
>
> .

In order to fulfill objective 1 theoretical literature concerning E/E architectures is analyzed in two major steps. First the foundations of E/E architectures with regards to the general structure are mapped out. Afterwards it is analyzed how this structure will change in the light of IoT and what challenges are associated with these architectural changes.

4.1. E/E Architecture Foundations

In this chapter E/E architectures are discussed as a sub-field of product architectures. First definitions used in literature for E/E architectures are presented in order to give an overview of what it is meant in this thesis when referring to E/E. Secondly, it is presented how these architectures evolved over the last decades and lastly a generic description of E/E architectures is derived, which is used as a reference in this thesis.

4.1.1. E/E Architecture Definition

The term E/E utilized in this thesis refers to electric and electronic components. Electric regards to electro mechanical components such as actuators whereas electronic refers to components only based on electrical principles such electronic control units (Brandt, 2016). Considerations regarding E/E architectures are mainly used in the automotive and aerospace industry, where it is used in rather different ways. Raue et al. (2014) for example define E/E architectures in the automotive area as

> “[...] the interfaces, the structure and the interaction of the networked E/E components, the power distribution and the wiring harness”.

Jiang (2019) on the other hand is using a definition referring to the general architectural definition used by the IEEE (2000) aiming to describe software-intensive systems:

> “[…] the fundamental organization of vehicle electrical and electronic components, including electronic control units (ECUs), sensors, actuators, wiring, power distribution, onboard and wireless communication etc., to realize the desired function and performance goals, with emphasis on the interactions and interdependencies among the components and with the environment, as well as the principles guiding the design and evolution.”

Following this definition shows that E/E architecture can be handled quite similar to the term of PA but focusing especially on E/E systems. Furthermore, besides having the physical E/E components, nowadays many architectural descriptions of E/E systems include digital software components, too. This is due to the fact that this is how certain functions of modern E/E products are technically implemented into the E/E system. Also Jiang (2019) states that the placement of software applications can be seen as a component of the E/E architecture. Brandt (2016) consents by noting, that rarely pure E/E based functions are applied anymore.

4.1.2. State of the art E/E Architectures

The term E/E architecture is especially utilized in the automotive and aerospace field. In the automotive area one of the major reasons E/E architectures caught attention was as a means for complexity management. Due to the fact that in this industry more and more purely mechanical components are substituted or enhanced by E/E components (Buechel et al., 2015). Moreover, E/E components are considered as the major innovation drivers in the automotive area. According to Robert Bosch GmbH (2014) 90 % of the innovations occurring in the area of motor vehicles are based E/E systems. Furthermore, during the last years the application of E/E components spread across almost all possible domains in the automotive industry. In the automotive area the number of integrated microcontrollers has risen from 10-15 per car in the year of 1980 up to 120 – 150 per vehicle in the year 2005 (Robert Bosch GmbH, 2014). Due to the large complexity issues resulting from this development the term E/E architecture became prominent as a means to manage the many components and large varieties by for example integration mechanisms (Navale et al.) and platform development (Brandt, 2016).

The improvements of E/E architectures in the automotive field are assumed to be representative for many different industries, where complex E/E systems were implemented over the past decades substituting or enhancing mechanical components. However, automotive E/E architectures are most likely the most complex of their kind and thereby represent a rather extreme example.

4.1.3. E/E Architecture Description

The varying definitions outlined in chapter 4.1.1. show, that similarly to the general term PA discussed in chapter 3.1, there is no universally valid definition of the term E/E architecture either. Rather are the applied definitions always tailored for the specific purpose. Moreover, one major problem when aiming to map out a reference architecture is that E/E architecture descriptions utilized in the field of automotive and aerospace engineering are not only rather industry specific but also highly complex as described in chapter 4.1.2. Considering the fact that the research aims to be generically applied across different industries it is necessary to build an own interpretation of E/E architectures suitable to be applied in this thesis.

Nevertheless, the definitions discussed in chapter 4.1.1. represent a solid base for developing a more generic architecture description. In the definition utilized by Jiang (2019) the term E/E architecture is in fact used rather generic and there is no reason for limiting it only to the automotive field. Moreover, the definitions discussed in chapter 4.1.1. have in common that they distinguish between two technical layers: The hardware layer and the software layer. In fact, applying the highest level of abstraction these two technical layers can be seen as a highly generic E/E architecture description. At this basic stage all electric functions and electronics functions can be mapped in this generic architecture. The total set of E/E functionalities form what is called in this thesis the system functions. This highly abstract architectural description is visualized in Figure 2 and acts as a reference for further architectural descriptions and considerations regarding connectivity.

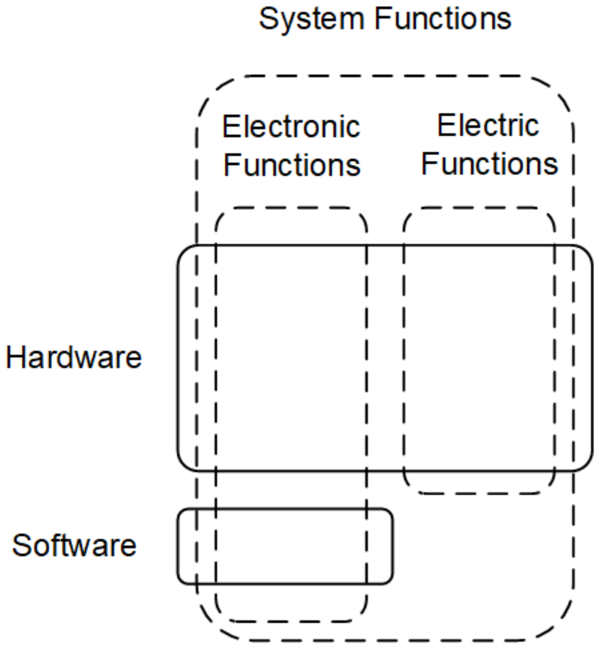

Figure 2: Basic representation of the two technical layers of E/E architectures and mapping of Electric and Electronic functions

4.2. The Impact of Connectivity

The previous chapter mapped out the structure of E/E architectures on a highly abstract level. In the next step it is investigated how this generic structure will change in the light of increasing connectivity.

4.2.1. Implications of Connectivity

In general, the implications for future E/E architectures associated with increasing connectivity can be categorized into three major categories, which are depicted schematically in Figure 3. These are "increasing amount of software", "increasing importance of signal transmission" and "expansion of system boundary".

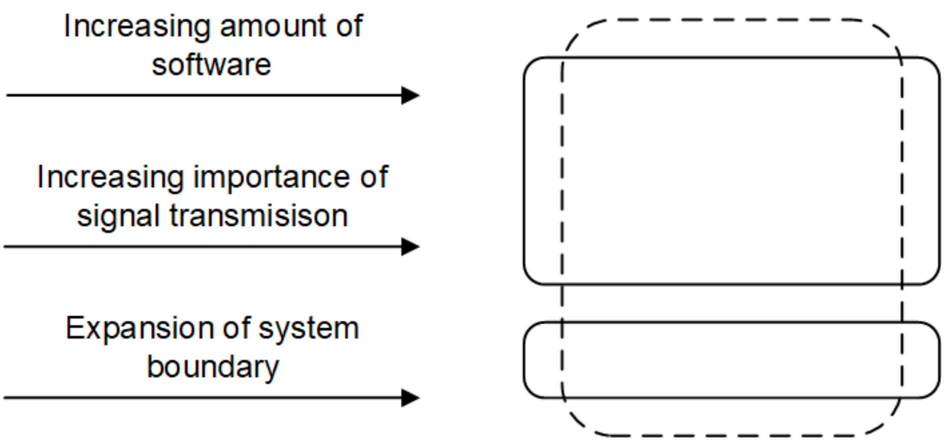

Figure 3: Implications for future E/E Architectures

The first major implication is the fact that E/E systems get more and more SW focused. This is however in fact rather general and not necessary only associated with connectivity and more driven by the general trend of digitalization. The general definition and architectural description of E/E architectures outlined in Chapter 4.1 implies that SW is already a crucial architectural component in current E/E architectures. However, it can be assumed that SW will gain significantly more in importance in architectures developed in the future. This development was already outlined in the year 2002 by Maier and Rechtin (2002), who mentioned a shift from "HW first" to "SW first" approaches, which underlines the importance of SW already during that times. They already described a shift in terms of development effort from 30 % dedicated to SW development and 70 % to HW development to a ratio of 70 % effort dedicated for SW development and only 30 % on HW development. Whereas this ratio initially only referred to telecommunications and consumer electronics Jankowski et al. (2014) stated several years later that the percentage of total investment in fixed assets for SW development was 2012 almost as high as into traditional capital goods. Moreover, SW functionalities can be seen nowadays from a new perspective than only contributing to the products main function. The possibility of sharing and processing of certain data of the product's usage is one example for a potential SW-based service offer. This turns pure products into product-service-systems according to the definition by Tukker and Tischner (2006).

Besides the fact that future products will be significantly more SW focused than in the past another significant shift can be observed directly related to increasing connectivity. Historically, the importance of the architectural components related to data transmission was rather unimportant in comparison to the often complex set of functions placed in the system layer. Furthermore, in most cases the main functionalities of the product were embedded into the actual physical product by mechanical and E/E hardware and software partitioned on electronic components. In the light of increasing connectivity, however the architectural components dedicated to signal transmission will gain significantly in importance. This is due to the fact that connectivity is becoming in connected products a necessity to fulfill certain functions. Porter and Heppelmann (2014) for example describe a home audio equipment manufacturer, who outsources the user interface of the product and the music source to the cloud. Those were previously implemented in the actual product by HW and SW components. Thus, in order to perform any control actions of the product it is required to be connected. Further, this example shows a case, where the architectural system layer decreases in its amount of functions and thereby loses in importance.

The third major implication when talking about connected products is based on the fact that companies have drawn their product's system boundary in a way that their product is something that is independent from its surrounding. However, in connected products certain functionalities are only enabled by connecting to the systems environment such as cloud platforms or other products. Porter and Heppelmann (2014) describe how the emergence of connectivity transforms stand-alone products to components interacting in a connected product system. Connecting standalone products to other system components might optimize their individual functions respectively or even enable functions not been possible to provide before.

4.2.2. Effects on E/E Architecture

In order to develop an understanding how the description of a connected E/E architecture might look like it is analyzed how the mentioned implications outlined in Chapter 4.2.1 impact the generic structure visualized in Figure 2 in Chapter 4.1.3.

First it was analyzed how “increasing importance of signal transmission” impacts the generic E/E architecture by examining functional architectures of historically connected products. Here, especially so-called consumer electronics (CE), which refer to devices such as smart phones personal computers or tablets are considered as the benchmark. Thus, literature describing different architectural models for consumer electronics is examined. Three examples for functional architecture description developed by Wolf (2012), Trew et al. (2011) and Mathews et al. (2017) are shown in Appendix 2. Examination of these three functional architectures shows that more than just system functions can be found. All three functional descriptions show that besides a system function layer as building the major element in unconnected E/E architectures, another functional layer dedicated with connectivity and remote data transfer is indicated. Wolf (2012) for example refers to a network interface in their functional block diagram, which can be either a rather simple USB connection or a sophisticated internet connection. Trew et al. (2011) refer to connection to peripheral or service providers. Mathews et al. (2017) simple use the representation of a gateway to distinguish it from the system layer or what they call it the applications layer. Thus, it is assumed that every other product featuring connectivity functionalities in the future will feature a similar functional architecture distinguishing between system functions and data transmission functions. Based on this assumption, the basic E/E architecture description mapped out in Figure 2 in chapter 4.1.3 is supplemented by another functional layer, here called signal layer as visualized in Figure 4.

Besides system and signal layers moreover the input-output (I/O) function layer is represented in Figure 4. In the functional description utilized by Trew et al. (2011) this refers for example to inputs/outputs generated/received by the users through a display, a remote control or mobile phones. The I/O function layer is in the architectural description shown in Figure 4 inside of the system layer. This is due to the fact that it is considered here more as part of the basic functionalities the system has to provide comparable to any other user interface as well, such as a mechanic lever or a mechatronics bottom. Thus, in this architectural description it is assumed that the I/O system is seen as internal PA interfaces, whereas the signal layers represents the interface to external services and products.

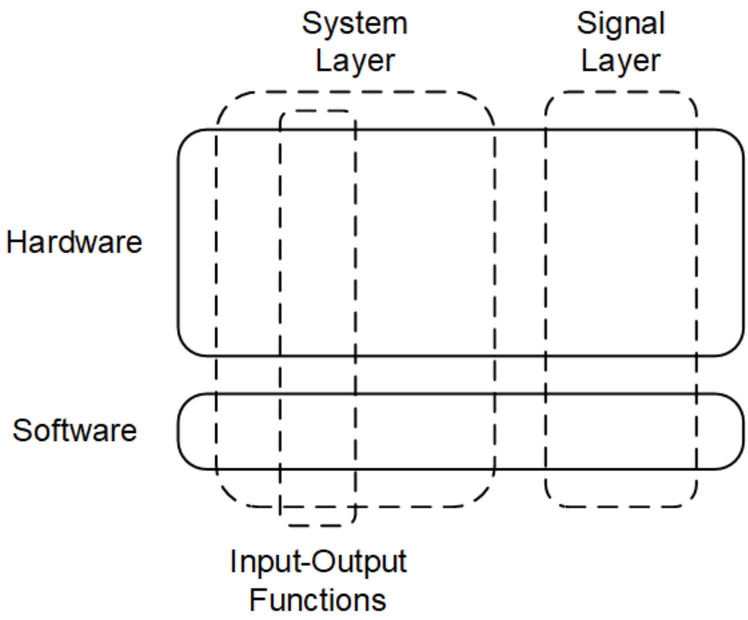

Figure 4: Extended architectural description visualizing the emergence of the new functional layer

Even though the architectural description in Figure 4 is derived from analyzing reference architectures of consumer electronics it is assumed that this architecture is valid for all different reference products to be analyzed, since it is still rather generic. Considering complex architectures such as those which can be exhibited in the automotive or aerospace industry represented by the description above would basically mean having a rather complex system layer and a relatively simple signal layer. However, the mapped out architecture simply aims to distinguish between system layer and signal layer enabling to map design characteristics respectively on the layers and compare their differences.

Referring back to the architectural foundations and definitions outlined in Chapter 3.1 it can be stated that in the light of connectivity the term product architecture utilized by Ulrich (1995) is less appropriate describing these new kind of products. Rather the architectural consideration of a systems architecture utilized by Maier and Rechtin (2002) seems more appropriate and must be used when designing product systems. As a consequence, shifting value creation from a stand-alone product to a connected product system. Figure 5 shows the expanded system architecture of a connected E/E architecture. Besides the architectural layers outlined in Figure 4 the expanded architecture description contains the network layer referring to the network used to communicate with other products, cloud platforms or IT systems.

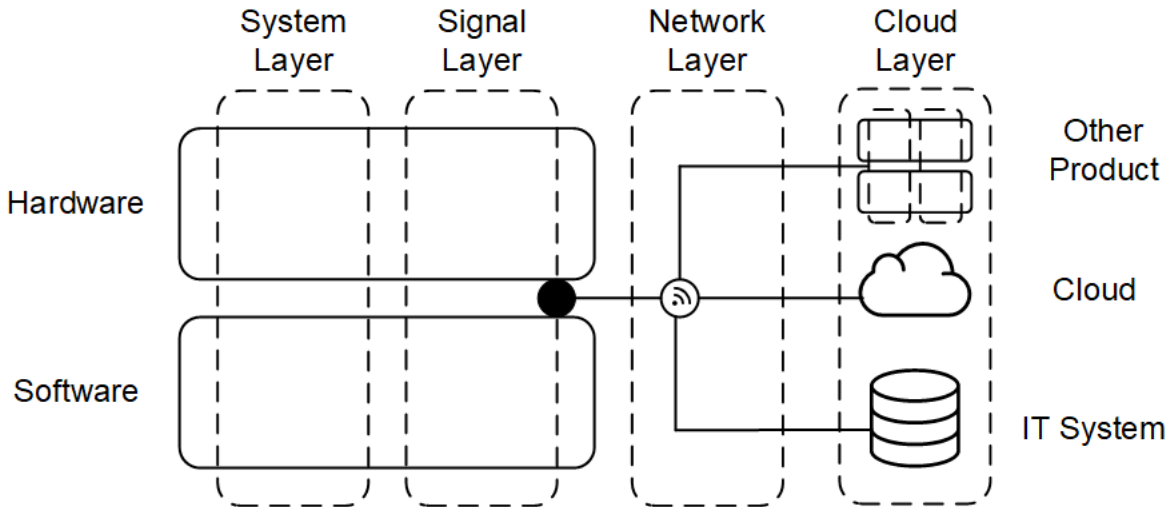

Figure 5: System architecture of a connected product system

Besides the actual design of E/E architectures and the defined system architecture increasing connectivity results in a set of architectural characteristics or quality attributes. Rahman et al. (2018) map out a set of quality attributes for IoT systems concerning the entire life time of such systems. Those quality attributed or architectural characteristics are: modifiability, interoperability, functional appropriateness, availability, usability performance, deployability and adaptability. Those attributes are comparable to the so called “ilities” as discussed by Crawley et al. (2004). Most of these characteristics of connected E/E architectures result from the fact that IoT systems, associated services and applications evolve continuously over life time of the product. This continuous evolution of the system is a great possibility for developers since connected products can be updated within operation stage of the product from remote places (Rahman et al., 2018). Further it is interesting since it enables faster lead times for the first roll out of the product followed by continuously delivered upgrades. On the other hand it is even a necessity due to the fact that in connected IoT system often devices are connected with significantly different life times. Streichert and Traub (2012) for example state that the connection of cars with consumer electronics is a really challenging development task due to the fact that consumer electronics only have a really short life time in comparison to the E/E system integrated into cars, which is designed to last up to 30 years. Thus, this requires that developers consider how to integrate future upcoming technological trends, which might not be known during the development of the connected product. In order to ensure that the product value generated from the integration of an ecosystem is assured throughout the entire life time of the product system the qualities mentioned above have to be assured.

4.3. Research Relevance E/E Architectures

In this chapter a generic description for connected E/E architectures was derived by outlining the most basic structure and then successively adding further architectural layers resulting from the increasing connectivity. Even though the derived reference architecture does not fulfil the aim of the thesis yet in terms of guiding design and development of connected E/E architectures it indicated that in comparison to E/E architectures in the past a multilayered architecture emerges.

The challenge associated with the emergence of these new functional layers becomes clear, when referring back to the fact that the existence of the system layer alone resulted in great complexity issues in the past such as discussed in Chapter 4.1.2. Further it must be considered that “complexity of implementation” is mentioned as one of the major barriers to overcome when developing connected products (Ganguli & Friedman, 2017). Thus, it can be concluded that connecting products already featuring a high degree of complexity in the past, will be an even greater challenge. This again shows the need to give guidance in terms of E/E architecture design and development to companies moving towards more connected products.

The reference architecture derived in this chapter, does however not only fulfill the purpose of putting emphasize on the challenge of growing complexity but also aims to facilitate processing the results gained in the interviews referring to significantly different products. Further, it will be especially interesting to investigate in how far design and development of the different technical and functional layers differs to each other.

5. Industry Study

By conducting an interview-based empirical study objective 2 of the thesis is aimed to be achieved, which is defined as:

> ***Objective 2:*** *Explore how R&D organization across different industries design and develop connected E/E architectures and understand why certain design and development approaches are chosen*

In order to fulfill objective 2 in the following, first the results are presented with regards to different drivers, design and development approaches the interviewed companies are following. Afterwards, it is analyzed why certain design and development approaches are applied in order to provide input to the subsequent model development process.

5.1. Results Industry Study

The following chapter aims to present the results from the interviews conducted with experts in the different fields.

Therefore first, it is presented how the different companies adapt to these trends, if they affect their product portfolio anyway and how far they are already in development. These questions were of high importance to state in the beginning since it affected the interview's pathway by defining how questions are phrased. Along with this it is discussed, what drivers were mentioned for initiating development activities. Secondly, it is presented how the different organizations aim to design their future E/E architectures in the light of IoT. Therefore, architectural characteristics mentioned by the interviewees are mapped on the E/E reference architecture's different layers outlined in Chapter 4.1.3. Lastly, implications on the development from an organizational and processual perspective are presented.

Since the interviewees set high requirements in terms of confidentiality neither the name of the company nor the interviewees' names are stated in this report. Instead, the interviews are numbered from 1 – 10. Table 2 provides an overview over the conducted interviews assigning the different interviews to a higher-level industry area and giving information about the different roles of the person interviewed. In total 10 different interviews were performed, whereas all interviews followed the interview guideline shown in Appendix 1 and took 45 – 60 minutes. Interview 8 was shortened due to limited availability of the interviewee. Moreover, interview 5 and 7 were conducted with the same company but interviewing persons from different departments and sites of the organization. When referring to this company both interviewees are working on it will be referred in form of "company 5/7". Considering the point of exit all the companies are comparable with regards to the fact, that all used to manufacture historically non-connected and analog products and having their core competences in mechanical parts.

Table 2: Overview of the conducted interviews with respective industry area, position in the supply chain, role of the interviewee within the organization and date

No.	Industry	Supply chain	Role Interviewee
1	Medtech	OEM	Director Engineering
2	Transportation	OEM	Chief Engineer
3	Vehicle	OEM	Head E/E and PMO
4	Household Appliances	OEM	Project Manager Connected Services
5	Agriculture Machinery	OEM	Supervisor E/E Systems
6	Production Machinery	OEM	Head Software Development
7	Agriculture Machinery	1st Tier	Principal Engineer, Worksite Architecture
8	Production Machinery	OEM	Head of Modular Product Development
9	Construction Machinery	OEM	Head of Mechatronics
10	Medtech	OEM	Head R&D Engineer

5.1.1. Adaptation of Connected Products

The second part of the interview aimed to provide understanding what the mega trend connectivity meant for the respective companies. Therefore, it was first asked if products with connected functionalities were already developed or planned in the past in order to characterize the adaptation level of connected functionalities. Second drivers initiating development activities are outlined.

Wirth regards to level of adaptation the interviewed companies could roughly be categorized into two groups. One group, which is already developing or already released first generation products exhibiting such features and the second group which is more hesitant about implementing such functionalities. Table 3 gives an overview about how the interviewed companies can be assigned to both these different groups.

Table 3: Level of adaption of the interviewed companies

No development effort yet	Connected products in development or first generation already available
Interview 2, 3	Interview 1, 4 – 10

In order to give a more detailed description of the current state of development the interviewed companies are mapped on the IoT maturity model outlined by Porter and Heppelmann (2014) mentioned in Chapter 1.1. Since this four-stepped model does however only categorize products providing already a minimum extent of connectivity with monitoring send-only functionalities as a minimum, the category “unconnected” was added in order to map all interviewed companies into this representation. Figure 6 gives an overview over the different levels of adaptation of connected functionalities. Further, the target state the interviewees mentioned development activities will focus on in the future is indicated.

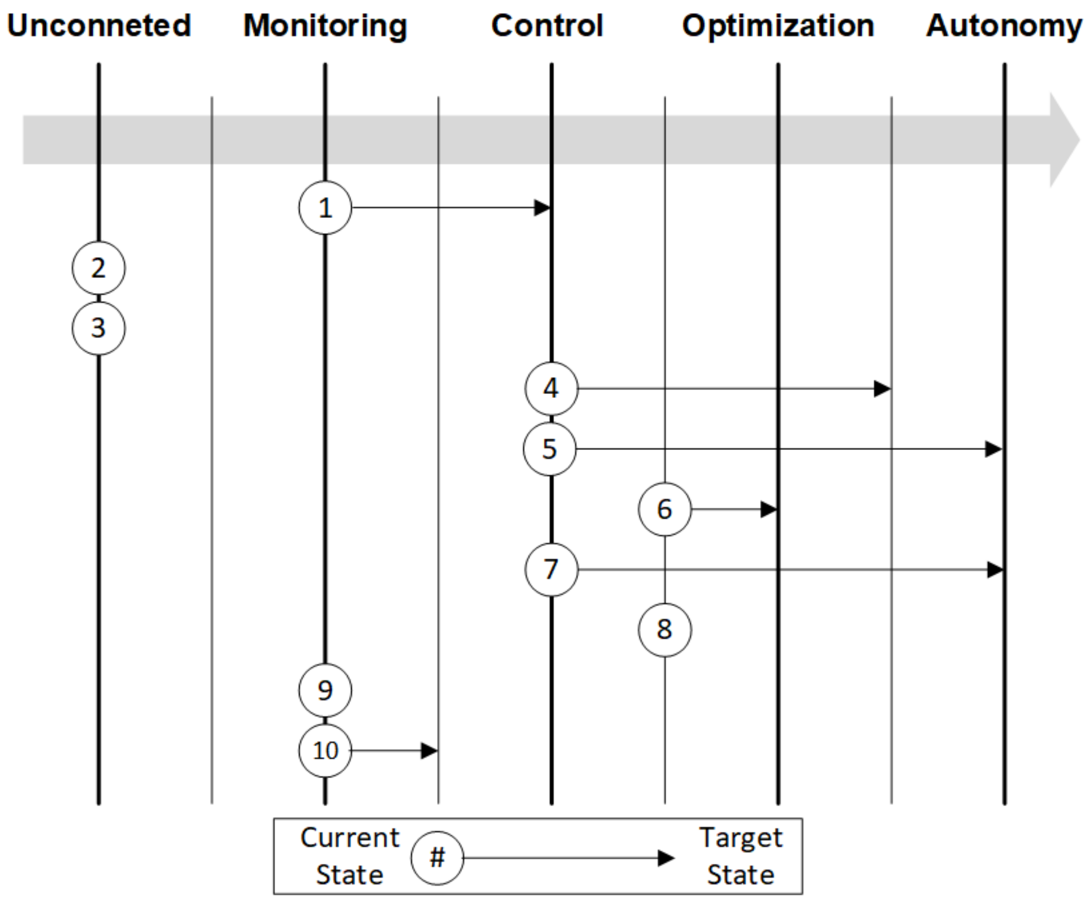

Figure 6: Illustration visualizing the current state of the interviewed companies and the indicated target state

When asking the individual companies about drivers for them initiating development activities and further choosing a certain maturity level of IoT two major aspects were mentioned by the interviewees. The first aspect concerned the fact that some companies mentioned that it was a highly strategical decision to start implementing connected functionalities. Secondly, some companies have stated that the initiation did not really come from their side and they rather have not had any other choice since their customers demanded providing certain connectivity. Thus, the drivers for initiation of development activities can be categorized into push factors coming from the companies and pull factors from the direction of the market.

Company 4 is one example, where initiation was based on strong strategic choice. In the area of household appliances, they predict that connectivity will have a great impact and offers many potential applications. This comes along with newly emerging business models by providing digital services. Company 4 intentionally started development activities towards more connected products in order to benefit from these newly emerging business possibilities. Moreover, they felt the need to initiate development relatively early since they stated, that large global players such as Google or Amazon would get into the market otherwise. Likewise, interviewee

5 and 9 stated that the development activities were based on purposely made strategic choices in order to develop new business models or improving product value for their customers.

In contrast, company 6 showed that they did not have the choice of initiating development activities from their side. Most of their customers are large manufacturers with complex connected manufacturing systems, who demanded company 6 to enable integration of their production machinery into their already existing production system. Thus, company 6 did not have any other choice than integrating connectivity functionalities into their product to meet their customer demands.

In accordance to these two categories of drivers initiating development activities in the different companies, the two companies, which have not stated development activities yet, mentioned that both forces are not existing, which prevented them from starting development activities so far.

5.1.2. Key Challenges for E/E Architecture Design

After asking the interviewees about the impact of connectivity and associated drivers, the interview shifted to the more technical part focusing on challenges in designing future-proof E/E architectures. The interviewees were asked in a rather open question what they think the biggest challenges are in terms of architectural design. Figure 7 shows the three most mentioned challenges and the number reference of the interview it was mentioned in. All these challenges were mentioned by four different interviewees respectively.

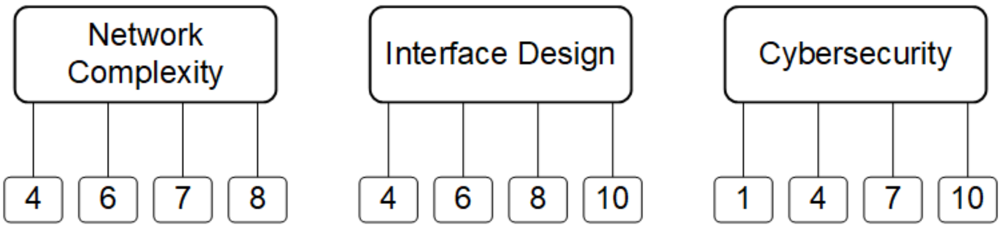

Figure 7: Key challenges pointed out by the interviewees. Numbers indicate the interview it was mentioned in.

Referring to the general E/E architecture description it becomes visible that all these three top named challenges can be assigned to the functional architecture layer stated as signal layer, which shows the importance of this functional layer when moving towards more connected product architectures.

5.1.3. Design Implications and Architectural Focus Areas

In terms of the results concerning the design of future E/E architectures one major challenge was that the different interviewees were referring to significantly different products and corresponding architectures. Moreover, the way the interviewees interpreted the term E/E architecture seemed to show differences due to fact that some interviewees were considering it more from a HW perspective, whereas others rather addressed architecture design of the SW. Further, some statements were even so generic and referred to both technical layers such as the case, when interviewees were talking about interfaces or gateways of their products. In order to deal with these issues the generic reference architecture for connected E/E architectures developed in Chapter 4.1.3 was utilized to categorize the results by mapping the mentioned characteristics into four architectural focus areas, as shown in Figure 8.

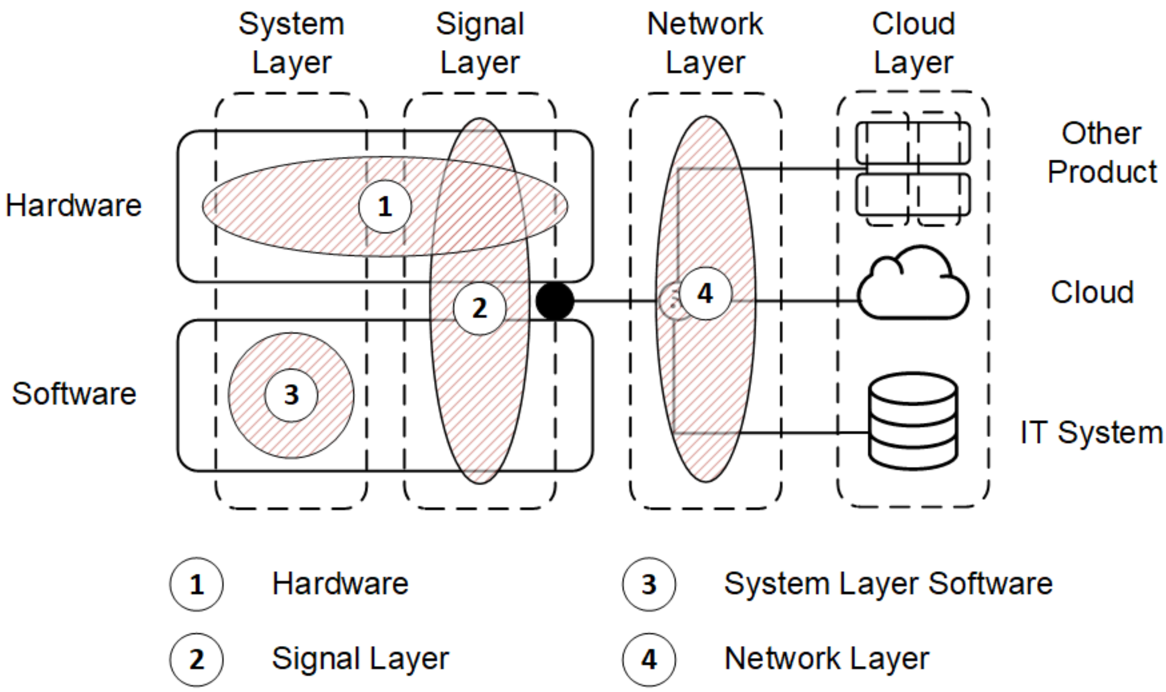

Figure 8: Architectural focus areas in connected E/E architectures addressed throughout the interviews

The architectural focus areas for connected E/E architectures namely are:

- Hardware
- System Layer Software
- Signal Layer
- Network Layer

Besides these four architectural areas, some answers regarding design referred to a more abstract architectural aspect, which does not concern any of the functional or technical layers outlined before. Those aspects were concerning rather the actual system definition such as how the "boundary of responsibility" of a firm is drawn in a connected system.

In the following it is presented what the experts from the different industrial areas interviewed stated to be important when designing future proof connected E/E architectures. The answers are thereby assigned to the architectural focus areas as outlined in Figure 8

System Definition

The most fundamental criterion, when comparing the utilized architectures of the different interviewed companies lies in the fact how the different companies set their own system boundary. When saying "own system boundary" here not the point where a system ends is meant and rather where a company's direct development responsibility ends. As already outlined in Chapter 4 it is in the nature of connected E/E architectures that they cannot be seen as a stand-alone physical product anymore and thus rather are seen as a system architecture. The reason for this way of thinking was clearly outlined by interviewee 4:

> *“By developing a working product ecosystem increased customer value could be achieved, which would not be possible to create as a stand-alone product”*

Thus, when trying to design a connected E/E architecture it is always a question of system expansion or where to draw the line for own component responsibility within the system. This is important for companies to define, due to the fact that it was shown in the interviews that it had a major impact on the other architectural element of the product system. Again, this does not necessarily mean the system becomes smaller or has fewer components. It rather has an effect on the fact how many internal or external development activities are included in the system.

A major difference in system definition was seen for example when comparing Interview 4 and Interview 6 with each other. Company 4 had the intention to implement digital services into their product portfolio of household appliances. Moreover, they developed them mostly on their own in order gain the maximum benefit out of this combined product service system. However, this also means they have to expand their system view and associated product responsibility to the furthest extend, which among others meant that they had to develop their own cloud platform and mobile applications.

Another way to set the system boundary was presented by interviewee 6, who had the integration of their production machinery into their customers’ production system as a clear customer requirement. Thus, the did not really had the choice to expand their system boundary as much as they wanted to, and it was rather set by their customers, who is responsible for large parts of the connected infrastructure. Thus, their system responsibility is still focused on the physical product like it was before.

Figure 9 visualizes the differently set system boundary comparing the level of system expansion between company 4 and 6.

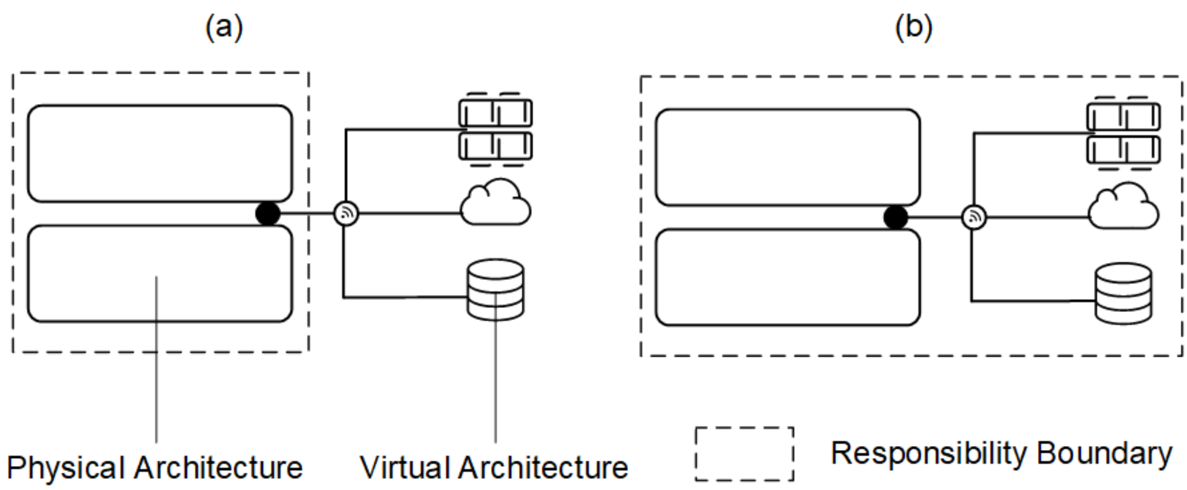

Figure 9: Comparison system boundary expansion between products from company 4 (b) and company 6 (a)

Another architectural property on the system level became visible when looking on the fact how much functionalities are placed in the actual physical product and how much are placed in virtual facilities such as the cloud or external IT systems. This results in the fact that IoT products in general can range from hardware-focused to cloud focused-architectures. This distinction for example becomes visible by comparing the products of company 4 and company 9. Company 9 is using connected services simply in form of transferring product data such as needed for maintenance to the cloud and did thereby only move data storage functionalities. Those were historically located in in the physical product. However, due to the fact that their construction machinery products are utilized in regions, where no network is available they cannot fully rely on the connected functionalities and still enable local data storage. Thus, this architecture is nevertheless still rather hardware focused, since most of the functionalities are embedded in the physical E/E architecture and disconnection would not limit the product's function significantly.

In contrast, looking on the product vision presented by interviewee 4 shows an architecture moving towards a more cloud-based architecture. The products in development already include functions such as automated cooking functionalities for certain recipes, which are only accessible by utilizing the associated mobile application. According to interviewee 4 the company aims to increase this cloud-focus in the future even further by replacing all physical buttons and controls entirely by a fully virtual interface. In this case most of the functions of future household appliances would be dependent on the connection to a digital user interface. The incentive of transferring functionalities to the cloud is in this case to centralize control functions of different products into one central user interface and further achieve higher possibilities for automation. Another example how functionalities are spread across the system, however due to a different purpose was mentioned in the interviews 6 and 8, where so called on-premise SW applications were utilized. These on-premise SW approach enables improved performance, by instead of running SW on the less powerful computing units of the product, running it on centralized powerful computing facilities of the respective production facilities.

Applying these distinguishing categories to the interviewed companies it can be seen that quite much all of the companies except of company 4 still tend to utilize hardware-focused architectures. This is however not necessarily surprising due to the fact that the entire set of interviewed companies was historically purely product-focused companies only occasionally implemented service contracts in some B2B constellations.

Hardware Architecture

One of the major questions regarding hardware architecture was how to deal with upgradability and extendibility from an architectural perspective. This was for example expressed by the architectural quality attributes outlined in Chapter 4.2.2. This need also became evident throughout the interviews. In total 8 out of 10 interviewees responded that they deliver regular upgrades to their SW. Moreover, 5 (company 4 – 8) out of 10 interviewees stated that they are planning to implement completely new SW functionalities to their products already existing on the market. Further, upgradeability plays an important role due to the fact that connected product architectures often include consumer electronics such as used by company 1 and 4 to run mobile applications. However, consumer electronics have in comparison to the various product categories from the different companies interviewed both relatively short development cycles and lifetimes. Depending on the product the interviewed companies stated to have product lifetimes from 10 (Interview 6) up to 30 years (interview 9). Having such a big difference in life time means that there is the possibility that a technology gap arises within the lifetime of the product. This might result in incompatibility of the two components in the product system and consequently result in the fact that the product becomes obsolete too early. Interviewee 1 mentioned that this was a major issue, when they were trying to develop a mobile application for monitoring of the service status running on Apple's iPhone. Since Apple was constantly releasing SW updates and even launched new product generations, they could not keep up with their development pace. This challenge was summarized by interviewee 10 representing a company from the Healthtech industry by the following quote:

> "Here two worlds are meeting, which are not supposed to meet from the first place."

Both these factors force companies to rethink exchangeability and upgradability during the lifetime of the product in order to hold their products longer on the market and ensuring the full set of functionalities. Interviewee 4 talked about this case by stating, that the household appliances they will be selling in the future probably will have a significantly reduced life time due to this fact. He predicted it to be a problem since their customers might perceive the product with a shorter life time as having lower quality. A future fridge for example might last only 10 years and not several decades as their customers were used to.

In general, two different approaches where utilized by the different companies dealing with the challenges arising from adding functionalities in the usage phase.

The first approach to keep up with newly emerging technologies throughout the life of the product was to upgrade connectivity related HW components in course of the products' service and maintenance offer already existing. This approach was for example followed by company 5/7 and 6. In contrast, interviewee 1 on the other hand mentioned that this approach is not possible based on their currently applied product architecture. Nevertheless, he admitted that it will certainly play a role to exchange connectivity modules once technology is evolving. One of the reasons why exchanging the components is not possible in their case is that they are using the Bluetooth communication module which is integrated by default in the ECU provided by their sub-suppliers. Thus, the low development depth, limited their control over the component's architecture. Interviewee 4 stated that this would certainly be a possible approach in order to prevent their problem associated with reduced life time. However, he admitted that nobody is looking into such development activities right now by preparing the electrical hardware architecture for such changes, since this is rather uncommon in B2C customers relations. In general, it could be seen, that especially companies with B2B customer relations seemed to deal with these challenges more easily. This is due to the fact that their long-lasting products in many cases already had some sort of service integrated throughout the life-time such as exchanging certain components in terms of failure.

Another approach how upgradability is ensured from a HW perspective, is to plan for additional capacities unused during rollout. Interviewee 10 suggested that this could be reached either through implementing unused HW components such as sensors or leave spare interfaces in the architectures where HW could be integrated. Likewise, interviewee 4 mentioned that such unused capabilities were strategically used in one of their connected products before. They were selling a stove module, which did not have any automation functions during roll out. Nevertheless, it already featured the entire HW required for running applications planned for the future. These automation SW functions were gradually added to the product utilizing the spare HW infrastructure. This approach is most suitable if there is already such an application planned. Further, the customer has to support these development activities by for example willingness to pay for these extra capacities. This issue was mentioned in interview 2, where it was said that their customers are relatively hesitant in terms of innovation and are not willing to pay for such additional capacities.

Furthermore, modular electrical hardware architecture does not only play are role during a product's use phase, but with regards to the development between different product generations or derivatives. Especially, interviewee 10 stressed on this fact, by stating that the product architecture they are applying does not allow for radical changes due to its "rigidness", which could be interpreted as an integral architecture. He stated that they do not have the organizational capabilities associated with changing the architecture drastically, which only allows incremental changes of the product architecture. Furthermore, he mentioned that it is important to ensure technological agility or flexibility, due to their relatively small size resulting in weak market position. Due to this position, they are not capable to dictate design requirements of certain components suitable for their specific product in comparison to rather important customers such as automotive companies. He concluded that a modular architecture would be necessary to compensate the rapid technological market driven changes, which especially occur due to the fact that technology in this field is rather immature.

System Layer Software Architecture

As described in Chapter 4.1.1 SW is an essential part in E/E architectures and only the coexistence of both HW and SW enables the innovative value giving functionalities. Since it is out of scope discussing this architectural focus area in its smallest detail the interviews focused on questions regarding upgradability and scalability of SW functionalities. This is on the one hand especially interesting in the context of connected products due to the ease of implementation and on the other hand since this also touches upon the E/E HW. Further, it must be annotated that this section does only refer to the software concerning system functionalities such as visualized in Figure 8.

Since upgradability and extendibility are often referred to as significant advantages of connected product concepts in course of the interviews it was tried to understand in what extent the companies developing connected products are taking advantage of these capabilities. Therefore, it is first important to distinguish between the two terms upgradability and extendibility since it was shown that the interviewed companies used them to a varying extent. All of the 7 interviewed companies developing connected products are utilizing upgrades in order to frequently update their already existing SW functionalities from a SW maintenance perspective. Extendibility on the other hand, which is here understood as adding completely new SW functions during the lifetime of the product, is utilized to a rather different extent. Company 4, 6 and 10 stated that they either already released or are developing products with limited functions during the rollout. They are however successively extended during the life time of the product. They stated, that this approach benefits two sides. From the manufacturer's perspective they are able to cut product lead times due to the fact that less functions have to be developed until roll out and the customer benefits by continuously having the ability to integrate enhanced features. A major disadvantage however mentioned especially by company 6 in association with this SW extendibility approach is the fact that ensuring the compatibility of the newly added functions and already existing functionalities results in increased complexity. Interviewee 5 mentioned that company 5/7 is generally following a similar approach, however their marketing strategy requires to have a rather sophisticated set of base functionalities right from the beginning in order to justify their position as a premium product manufacturer. This significantly differs from company 4's case, where they released a product with almost no SW functionalities at the beginning, which then were continuously scaled.

In contrast to this rather agile extendibility type, company 9 presented an approach limiting the flexibility especially from the developers' point of view significantly, however is avoiding complexity issues on the other hand. In order to provide their customers more sophisticated functionalities beyond the basic set already included in the product system by default, they enable their customers to active or deactivate certain SW functions on demand. These functions are however already preinstalled during roll-out of the product, which avoids the mentioned complexity issues related with compatibility of new and old SW functions. Besides avoiding complexity issues another reason for this was that their products underly high regulations in terms of safety. This makes it for them more complicated to add functionalities into a certified system.

Signal Layer Architecture

One of the most mentioned elements in future connected E/E architectures resulting in challenges is the design of the signal layer and the associated interfaces. 8 out of 10 interviewees mentioned this aspect when asking them about challenges in development next generation connected products. Thereby, the interviewees defined different requirements or approaches for designing the signal layer in connected architectures, which however varied among the respondents. Due to the fact that a highly technical description of the interfaces is out of the scope of this thesis the classification of the interviews is again more on a functional level by stating qualitative design characteristics trying to describe the interfaces from both SW and HW perspective.

The interviews indicated, that a crucial aspect influencing the design of interfaces was the fact whether the companies were applying an open or a closed system architecture.

Company 6 set their responsibility boundary quite narrow around their actual physical product and does not develop a virtual platform on their own. Instead, their various customers such as from the automotive area require them to integrate the company's products into their connected production system. However, each of their different customers applies their respective production system ranging for example between a cloud or SAP production platform. This resulted in the fact that requirements on the interfaces differ significantly from customer to customer. Interviewee 6 put emphasize on the fact that in such a situation developing dedicated interfaces for each of their customers would not be feasible and would result in a large complexity issue. Their strategy to deal with these conditions was it to utilize an interface that is rather flexible and capable to accommodate to the different system requirements without adding additional complexity. This architectural approach can be referred to as an open system in the sense that it is possible to integrate company 6's product in different systems which maximizes the ease of implementation for their customers and creates an open-like architecture.

The connected household appliances ecosystem applied by company 4 on the other hand can be seen as an example for a closed system, considering the fact that basically all architectural components are developed by themselves including both the actual physical products and the cloud platform to be connected to. Only a few external developers are granted access to the platform to implement specialized applications to it. In order to ensure the maximum control over the system and ensuring the entire system is purchased from them the interfaces are not openly accessibly to everyone. This further results in the fact that the signal layer applied by company 6 is less driven externally. Company 4 thereby has more freedom in designing it accordingly to their internal needs. Nevertheless, interviewee 4 remarked that even if they set their own requirements they still have to consider the needs of their external development partners. An example for such a need, is the fact that the interfaces should stay relatively stable in the long term. Meaning changing the interface utilized by the external development partner too frequently could harm their development collaboration, since this is associated with updating their own products each time the interface changes as well. Thus, it is required to develop interfaces, which are relatively stable in the long term.

Moreover, the interviews showed that not only the fact whether a system is open or closed affects the design of the interfaces utilized within a certain architecture. The market position of company also plays a key role. Interviewee 10 illustrated this dependency by mentioning that their supplier relationship differs significantly for example in comparison to large automotive companies. Due to the large batch sizes related with working for automotive OEMs they can put much more requirements on the design for different components such as for example sensors and can even demand designing special components only for their internally defined interfaces, whereas companies like company 10 often have to deal with standard products out of the suppliers portfolio, which makes their interfaces highly dependent on industry generally used industry standards. Further this dependency requires them to think ahead in their design process and plan prospectively for up to 10 years which standards might be the most technologically sustainable in order to ensure the compatibility of their products for the required lifetime of the product.

In general, the interviews have shown, that regardless of the applied architectural system concept, companies should always think about which benefits standardization of their interfaces might bring for the products, especially with regards to increasing connectivity required from their customer. Interviewee 9 mentioned for example that utilizing a platform architecture moreover facilitates the collaboration with external partners such as the cloud provider they are collaborating with. Even company 4, which is performing a closed system approach mentioned that developing own branch-specific communication and interface standards comparable to the AUTOSAR standards (Fürst et al., 2009) defined for the automotive industry in collaboration with competitive household appliances manufacturers might be a necessary to provide a the united market significance to be able to compete with large global players in the area of digital services.

A point all interviewees agreed on was, that due to large number of different interfaces touching upon numerous different functions internally and externally on the same time it is even more important to clearly define the used interfaces for all involved parties. Interviewee 10 further remarked that if a company succeeds in defining their used interfaces properly it does not make a difference if the development tasks are performed only internally or in collaboration with external development partners. Interviewee 4 mentioned an external development partner, who did not have any technical questions during the development process thanks to the transparent definition of interfaces in combination with clearly defined deliverables facilitated the collaboration since unnecessary communication could be avoided.

Another point mentioned by many of the interviewees such as interviewee 1, 6, 5, 7 and 9 was the important requirement of considering cybersecurity within their system and especially when designing the signal layer. Interviewee 6 mentioned that this is especially in highly connected systems a great challenge due to the fact that the number of interfaces is relatively high and system components with very different system properties are connected with each other. Across the different industries the interviewed companies' emphasizing on cybersecurity concerns varied however quite much, which also depends on the fact how the requirements put from the legal side vary. The products of company 9 for instance have very high requirements with regards to functional safety due to the fact that malfunctions could be a risk for the operators, which is for example one reason for applying only one directional communication by send-only functionalities as further discussed below under the section network and data exchange. Company 1 is following a similar strategy due to high security risks in the data exchange interface. Securing these interfaces from a cybersecurity perspective is of course tremendously more complex than just defining requirements on it or restricting the direction of data exchangeability. However, securing the interfaces from a technical point of view is out of the scope for this thesis and thus no detailed questions were asked concerning this point within the interviews and emphasize was put on handling cybersecurity from a processual point of view.

Network Layer Architecture

The network infrastructure and connectivity type could be seen as the central part of IoT products. Again, comparably to the already discussed architectural focus areas, the choices in this one are highly dependent on the respective function of the connectivity resulting from its application the and technical infrastructure, too.

The first significant architectural distinction has to be made considering the type of network used to communicate and transfer data between the different elements in the system. This question is thereby first highly linked to the environment the different products are used in, since they provide different network conditions and on the other hand on the fact whether the product in its use phase is rather static or moving dynamically, within the use environment or even between different environments. The two big categories resulting from the different application are whether a local or a mobile network is used to communicate between the different elements. Moreover, the local network can be distinguished between WLAN or LAN connection. When not communicating via a network it is also possible to utilize communication standards such as Bluetooth. The interviews showed that it was preferred by most of the companies to communicate via a local network such as mentioned in interview 4, 6, 8 and 10. The products of companies 5/7 and 9 on the other hand have to communicate via mobile networks due to the fact that they are used normally in an environment which does not feature a local network.

The second criterion defining the network architecture concerns the direction data is exchanged, which has a major impact on the systems functionally. The data exchange can be either one-way in case of only featuring send-only or receive-only functionalities or two-way when both data is sent from the physical product to other system components and data is received in order to trigger actions. When referring to the IoT maturity model by Porter and Heppelmann (2014) it can be seen that the one-way monitoring function monitoring and thereby sending data only is one of the most basic functions in a connected system. However, this model does not consider that data can be send to a certain system without receiving data back from it. This was for example the first application connectivity was used in machines of company 6 in form of sending specifying data of a part to be produced to the production machinery. Referring, to this used maturity model it could give the impression that, this scaling from one-way sending functions to two-way sending functions is a gradual process, however the interviews have shown that not all companies following this gradual scaling approach. Products of company 1, 9 and 10 are following the approach of send-only as a first step in their transformations to a more connected product system. All of them see potential for two-way communication enabling control functions as well, however all these companies put high requirements on functional safety of their products and they do not feel the urge for implementation these functions considering the large development effort associated with their implementation for example in terms of cybersecurity. Company 4 on the other hand skipped the first level and developed connected products enabling remote control functions right away, due to the fact, that there were no suitable applications for them utilizing monitoring functions.

5.1.4. Development Implications

In the following challenges regarding developing connected E/E architectures are outlined. Hereby, it is distinguished between challenges first with regards to the way development companies are set up organizationally and second with regards to the actual development processes the companies are utilizing. At this place it should be mentioned that of course organizational and processual aspects are often tightly interwoven, however it is aimed to examine both these aspects independently. The implications presented in the following are hereby based on two different aspects covered in the interviews. The interviewed companies were asked on the one hand for challenges they encountered so far during development. On the other hand they were ask to define key success factors for companies moving towards increasingly complex and connected architectures. Both these aspects can be somewhat be seen as implication for developing these new product categories, since they deliver insights from different levels of maturity either referring to challenges they see ahead of them or challenges they already solved by a specific approach. Whereas the latter is even more valuable for the following discussion.

Implications with regards to development organizations

The first point, which was outlined by interviewee 4 as the most crucial key factors to success was that organizational structure should change from traditionally applied silo structures to a scaled agile organization. According to him the fundamental agile work procedures worked fairly well within the different smaller software development teams, however the teams were not empowered appropriately within the organization to be capable making the necessary decision for improving their continuously growing software architecture.

Another point were organizations have to change when dealing with the newly emerging development requirements was concerning the level of risk companies are willing to take. This aspect was mentioned by interviewee 10 and was based on his experience that the technologies associated with connected devices cannot be foreseen right now. This is due to the fact that this field is still relatively new and technology does change rapidly. Especially because company 10 is relatively small thereby is not in the position to define own design requirements to suppliers of certain connectivity related components they are heavily dependent on market standards. However, technology is changing rapidly in this area, which might result in the fact that companies relying on such standards have to take the risk that those might be outdated to some point. However, hesitation is according to interviewee 10 no option because waiting until technologies getting more stable would result in a large competitive disadvantage.

One aspect mentioned in several different interviews did not refer directly to the actual organization itself and rather on the organization’s external relationships. Several interviewees did mention the need for new external collaborations necessary in order to develop the new type of products effectively. Even though this aspect was mentioned by several different interviewees the underlying reasoning varied considerably for outlining the importance of extending external collaborations. One of the most commonly mentioned reasons for developing was certainly the lack of competences in terms of software developing with regards to the parts of the software architecture referring to connectivity related fields such as the cloud platforms. Here, company 6 and 9 especially outlined that development activities concerning a cloud platform does not touch upon their defined core competences, what prevailed them to outsource development activities in these fields. Interviewee 10 on the other hand stated that they simply do not have the organizational capabilities to build extensive software development capabilities in such a relatively short amount of time, which made them depended from external developers. Company 4 mentioned the importance of intensifying development collaboration from are rather strategic point of view. They did no expand their own product definition and included the digital services associated with their connected product into their product definitions, which on the downside resulted in the emergence of new competitors such as large digital global players providing their own connected home solutions. In order build competitive capabilities and being able to provide the same highly connected ecosystem and the customer value coming with this, interviewee 4 said that it is necessary to developments collaboration standards with other household appliance, in order to be collectively competitive. The last aspect where the need for external collaboration was pointed was however not directly related to development collaborations and more directed towards collaboration with mobile network provider, which is especially important for product finding application in remote areas not provide a local network. According to interviewee 5 and 9 their applications resulted in tremendous amount of data transfer, which resulted in high additional costs for these services in case no special serviced conditions are contracted with the network provider. Interviewee 5 put emphasis on the fact that this is especially challenging for smaller or medium sized companies since large network providers are not as interested in collaborating with them as they are with for example large automotive companies.

Implications with regards to development processes

Besides the mentioning of organizational implications, the interviewees were furthermore asked how moving towards more connected E/E architectures does affect the established development activities from a processual perspective. Insights gained from the interviews are presented with regards to this processual perspective are presented in the following. These aspects moreover are of two different types. First, aspects referring to the fact how processed have to be changes but also to which processes have be implemented additionally.

According to interviewee 4 one of the most fundamental processual aspect affected by increasingly connectivity is the fact way products are though throughout the design process. He stated when designing products in the future it is highly important to have constantly in mind that the value of created products is created through the entire ecosystem and not anymore by a set of standalone products.

Further, it should be kept in mind that connected products require to define lifetime responsibility form manufacturers for their already sold products in a new way since their reliable operation throughout the entirety of the intended lifetime can only be assured by providing continuous software upgrades especially with regard to the signal layer in order to keep cybersecurity standards up to the state of art. Thus R&D organizations have to understand that the development process of connected products does not stop after roll out. This aspect was mentioned especially by company 4, 5/7 and 9, with further annotating that that this life time responsibility required a drastically shift within the organization.

Another processual element to be considered mentioned in the interviews with company 1 and 10 concerned the fact how or better in which time horizon product value is created. Interviewee 1 mentioned that design and development decisions are in their company are mainly thought in in the short-term, which made them for example not thinking about the value of modular product architectures in the long term. Thinking development activities only in a set of successively following stand-alone processes, does not enable continuous improvement of the operation in the long term and prevents agile reaction to rapidly emerging technological trends. A similar concern with regards to the necessity of long-term thinking was raised by interviewee 10, who realized that their development processes so far only enabled incremental product changes, processing relatively slowly. According to him this led to rather “rigid” product architecture not enabled changes with ease. He however, foresees that in the future it will be necessary to adapt to market changes more rapidly especially due to the fact that their relatively small company forces them to adapt to changes for example in terms of technological standards to be used instead of dictating own requirements to markets and suppliers.

Interviewee 10 further raised another point how companies have to adopt their developments processes in order to deal with rapidly changing technological and ensuring perpetually value creation of connected ecosystems. Since he is foreseeing the need the for integration of new components into there system he suggest that not only a modular architecture should be applied also standardized processes of integration in a modular manner should be developed in order to keep the effort associated with the integration of new components manageable for medium-sized companies, which do rarely have the organizational capabilities to adapt flexibly and allocate large development resources on demand.

Whereas the implications for development processes so far concerned the shift of established development paradigms and a relatively high level some interviewees delivered rather specific suggestions for sub-processes, which have to be integrated in order to being capable to deal with challenges associated with the integration of connectivity-based functionalities especially with regards to the tremendously increased complexity. In general, interviewee 4 mentioned that connected E/E architectures require effective complexity managements more than ever before. This is due to the fact that through the increasing amount of software being part of products, not a large variety of E/E components has to be managed but also the large amount of digital variety in form of differing software components. A specific means playing a crucial role in future E/E development project mentioned by both interviewee 4 and 6 will be enabling digital testing of the connected product system before the actual implementation. This for example comes to play in the case of integrating new updates into a system and checking preventively if this upgrade will work together with all other already existing components of the system.

5.2. Industry Study Analysis

The conducted industry study delivered a great amount of information concerning different drivers and challenges but also various design and development approaches for connected E/E architectures. In this last part of this chapter the gained data is analyzed holistically. First, general insights regarding the newly emerging signal layer are discussed. Afterwards, the results are analyzed with regards to derivations to be used in the model development process.

5.2.1. Differences Architectural Layers

In general, it could be seen that the different architectural layers mapped out in the connected E/E reference architecture in Chapter 4.2.2 exhibit significantly different design characteristics and are associated with different development challenges. The defined architectural focus areas utilized to categorize the interview results cover all the mapped out technical and functional layers. Further not only the identified characteristics mapped on the different layers differ, but also the number of characteristics assigned to each respective layers differs significantly. The architectural layer with the most characteristics to considers is clearly the signal layer. One reason for this is presumably the fact that the signal layer is affected by two architectural focus areas at same time, as it can be seen by the overlapping area in Figure 8. This results in the fact, that the design of this functional layer gets rather complex since several different aspects are influencing it.

The complexity of designing this architectural layer can further be seen by the fact that all three top mentioned challenges are somewhat associated with the signal layer and the corresponding system interfaces. Further one interesting fact is that issues in designing the right interfaces was mentioned by very different roles across the industry study. Therefore, it can be concluded that the difficulty designing the system's signal layer regards to both HW and SW development.

5.2.2. IoT Architecture Archetypes

In chapter 5.1.3 it was outlined how the different companies are designing their connected E/E architectures. It could have been seen throughout the set of conducted expert interviews, that in fact the way connected E/E architectures are designed varies across the different industries with regards to different architectural aspects. Besides this finding the question still is if between the varying factors major similarities can be exhibited. Such similarities in the architectural design would enable the definition of E/E architecture archetypes. This would be of great usage in the subsequent model development process since it would enable consolidating the gathered data into smaller better manageable set of characteristics.

Indeed, indications of the emergence of such architectural archetypes could be seen throughout the interviews, however the small number of conducted interviews raises the question if this is a valid basis to define archetypes on. Further only 7 different companies were able to be studied, which already had experience in developing connected products From these 7 different E/E architectures at least 4 significantly different E/E architectures could be identified, which consequently also results in 4 potential archetypes for connected E/E architectures. This however, would mean that there are only 1 – 2 examples for each archetype. Moreover, the companies interviewed are historically quite similar with regards to their starting point coming from mostly unconnected and rather mechanical focused products. However, as mapped out in chapter 1.1 there are numerous products with significantly different use cases, where for example the actual product does not play such an important role anymore. Investigating the E/E architectures applied in these cases would most likely result in even more potential archetypes. Both these factors result in the fact that a definition of archetypes based on the conducted set of interviews would first lead to a probably rather uncomplete set of archetypes and second this uncomplete set of archetypes would have relatively few evidences due to the small sample size.

This results in the fact that the development of connected E/E archetypes is not followed further. Especially considering the fact that these archetypes would have been used for the purpose of model development in later stages of this research the uncertainties associated with such barely fact-based archetypes are too high.

5.2.3. Study Result Hypotheses

Despite the fact that no E/E architecture design archetypes can be derived from the interview results, certain derivations from the results are necessary to process the large amount of data further an make the insights utilizable for guiding design and development activities. Therefore, two result hypotheses are constructed, enabling further processing of the data.

Architecture Definition Hypothesis

Part of the aim of the thesis to investigate in how far the E/E architectures differ across different industries. This implies that E/E architectures design mainly depends on the industry they are developed in. Indeed, some interviews such as interview 6 and 8 show that certain similarities can be observed, in one specific industry. However, on the other hand interview 1 and 10 have shown significant differences in the way the respective companies in the health technology area design their product architecture. Thus, it is assumed that classifying product architectures only based on the respective industry does not deliver necessarily always the same architectural design characteristics.

This twofold observation that in some cases architectural decisions somehow depend on factors associated with a specific industry but on the other hand cannot be limited to this single aspect, raise the question what more factors architectural design decisions depend on. Answering this question can be for example clearly seen when considering the business model company 4 is following and thus building their architecture on. Rather than having strong external factors forcing them to deliver certain connected functionalities, they strategically intended to broaden their product portfolio from only physical products standalone products to a more ecosystem-oriented product system. Likewise, company 5/7, 8 and 9 stated that there is not a pull by market requirements only and purposely made strategic decisions initiated development activities, too. Coming back to the question what the design of E/E architectures also depends on besides requirements associated only with a specific industry, it can be said that the interviews intent that the design further depends on strategic decisions. This involves for example strategy forming decisions regarding what elements of the connected E/E system is developed internally and which elements are developed in collaboration with external development partners or suppliers. But also, the differently followed approaches whether a step-by-step slowly scaling approach along the different maturity levels of IoT such as classified by Porter and Heppelmann (2014) is followed or if companies start on a relatively high level of maturity could be seen as a strategical decision resulting in different requirements for E/E architectures. This could be for example be seen by comparing the respective PA applied by company 9 following a step by step approach and that one from company 4 starting on a relative mature IoT level enabling control functionalities right from the beginning, when they started developing their connected product portfolio.

Considering the strategy impacting E/E architectures as a push force coming from the company itself the already mentioned factors associated with a specific industry can be seen in contrast as a pulling force coming from the industry specific market setting certain requirements. Crucial requirements defined by the market can seen in highly regulated markets setting many detailed specifications in terms in aspects such as functional safety which is the case for company 9. Moreover, a specific industry is often further associated with rather characteristic customer relations such as whether a business-to-business or a business-to-consumer costumer relations is followed in the specific market. But also, the variety of different customers and the associated varying costumer needs in terms what the product should be capable to do or when acting in a fairly connected world rather requirements concerning what the product should connect is affecting the architectural design significantly, as seen in the interviews with company 6 and company 10.

In summary, it can be assumed that rather than stating as in the beginning of this thesis that architectural characteristics of connected E/E systems are dependent on industries, based on the interviews it seems more appropriate to define it on a more abstract level namely assuming that the two categories strategy and market somewhat correlate with architectural design decisions, which from now on replaces the initial research questions focusing only on varying characteristics across different industries.

> **Result Hypothesis 1: The design of connected E/E architectures is heavily driven by the conducted strategy of a development company and prevailing market relations and requirements**

Architecture Development Requirements Hypothesis

Besides defining in detail what product architectures are, chapter 3 outlined the strong interdependencies of architectural design and overall performance measures of development organizations. Moreover, it was described that different architectures automatically affect organizational structures and development processes of existing in companies. Thus, it can be assumed that on the other hand drastic architectural changes also come along with somewhat changes of organization and processes.

These findings from the literature can also be seen, during the set of different interviews. As described in chapter 5.1.3 and 5.1.4 the interviews have shown that the different companies put emphasize on different organizational or processual aspects, which played a role in in the development of their future planned connected E/E architectures.

One example for such observation was mentioned by Interviewee 4. He outlined that the development of connected products requires them to transform to an agile organization. This is mainly due to the fact that their architecture is rather agile either in terms of continuously delivered upgrades, which only works if the development teams responsible for such these upgrades move agile within the organization. In literature similar correlations are outlined such as by Göpfert and Steinbrecher (2000), who state that modular architectures can only by used effectively, when the organization features modular characteristics either.

Thus, it is assumed further that the fact that the interviewed companies were designing various types of architectures, also lead to fact that they have to adjust their organizational structure and development processes differently. This leads to Result hypothesis 2.

> **Result Hypothesis 2: The way development companies, have to adapt from an organizational and processual perspective depends on the characteristics of the applied E/E architecture**

6. Model Development

In the last step of this research the results gained from the interview are further processed in order to achieve objective 3, which was defined as:

> ***Objective 3:*** *Consolidate the findings regarding design and development of connected E/E architectures into a conceptual decision model to guide design and development activities of companies moving towards more connected products.*

Therefore, the interview results are processed by making use of the two result hypotheses derived from the interviews and building the model based on these correlations.

6.1. Modelling Theory

Before start developing the actual model, briefly the theoretical foundation for such a model is outlined including remarks regarding modeling in general and short explanation of relevant modelling techniques utilized in course of the subsequent model development process.

According to Wynn and Clarkson (2018) especially design and development processes are associated with many challenges in terms of managing them properly. In such cases models enable to understand, support and improve such processes. However, the authors also state that generic models for every purpose rarely exist considering the fact that they are in many cases developed for a specific purpose. They further outline that models addressing design and development process are challenging to develop due to the fact that design and development processes naturally include the elements novelty, complexity and iteration. However, Gonnet et al. (2007) state that the development process of even rather different kind of products exhibits to some degree common characteristics, which can be worked out. In this thesis such distinct characteristics are aimed to be worked out for the design and development process of connected E/E architectures.

Besides this general complexity in the modelling process, the aimed model in course of this thesis indicates to be particularly complex. The literature study conducted in Chapter 4 concluded that the already rather complex E/E architectures will in future feature an additional functional layer adding further up to this complexity. The empirical study moreover showed that there is clearly no silver bullet approach for designing and developing future E/E architectures. A technique used in this modeling approach to deal with this prevalent complexity is the usage of a design structure matrix (DSM) which is a common tool in designing, developing and managing complex systems structures (Eppinger & Browning, 2012). A DSM is a tool to model networks and thereby analyzing the interaction of the various system components. Since, it proofed to be capable to model architectures in various systems ranging from physical products to organizations, it seemed rather appropriate to deal with the complexity prevalent in this research. Besides the fact that a DSM can be utilized as a means for a interdependence analysis, the results gained from the matrix can be analyzed further by utilizing the quantitative aspects of the matrix. Thereby, the interrelations of certain criteria with the entire set of criteria is examined. This can be done by utilizing means of structural complexity management such as outlined by Lindemann et al. (2009). For further analysis of DSMs, utilized in structural complexity management the authors define the so-called active sum and passive sum as characteristics for nodes and edges. These respective characteristics basically sum up the amount and intensity of effects an element in the matrix has on all other elements (active sum) on the one hand and on the other hand the amount and intensity of dependencies an element has on all other elements on the matrix. By analysis these parameters, it can be analyzed which of the numerous defined criteria have the biggest impact and which are rather sensitive because they are dependent for several different elements.

6.2. Model Purpose and Requirements

Before starting the actual model development process, it is important to recall what the model's purpose is on the one hand and on the other and what the delimitations are. Furthermore, similarly to every development process a set of requirements is outlined guiding the development process.

The model is supposed to give guidance to companies aiming to move their product portfolio towards more digital and connected products. Further, it is especially addressed to companies, which do not have the expertise in developing complex products before. First, the model is supposed to give suggestions on how to design E/E architectures referring to the different architectural focus areas, displaying the highest importance according to the conducted interviews and mapped in chapter 5.1.3. Secondly, suggestions are to be given with regards to the fact how R&D organization address challenges associated with the development of this new type of products from a processual and organizational perspective.

Along with outlining the model's purpose it is also crucial to clearly outline whom in a company the conceptual model is addressing and is supposed to help in making decisions. Due to its rather abstract nature the model aims primarily to give guidance to R&D mangers or system architects making strategic decision concerning, which direction the E/E architecture design should head to by having market need or strategic decisions in mind. On the other hand, it does not provide advice concerning technical details of specific components of the product and thereby does not address hardware or software developers in terms of finding the most appropriate technology.

In order to provide the aimed value in course of this thesis, for potential users and also acting as a basis to build future research activities four requirements are defined, which have to be considered throughout the model development process. These requirements regard to usability, visual representation of the model, quantifiability and scalability. These requirements are further explained in Table 4.

Table 4: Model Requirements with explanation

Requirement	Explanation
Usability	The model is supposed to be used only with the information provided in this thesis in order to provide value to companies with no experience in this field before

Visual Elements	Model is supposed to contain to some extent visual elements in order to facilitate usage and make results easily accessible
Quantifiability	In order to ensure reproducibility of the usage and potentially enable quantitative comparison the model is supposed to feature quantifiable elements
Scalability	Due to the explorative nature of this research the model is not fully complete and thus is supposed to be scalable by adding further information in the future

6.3. Model Type Selection

After outlining the overall purpose of the model and defining a set of requirements the next step in the model formulation process is to define an appropriate type of model to map out the varying results gained from the interviews and make them accessible for potential users of the model. Since the process of modeling is associated with varying levels of abstraction the process is not necessarily straightforward and there is not a defined set of models to choose from. Due to this fact a certain degree of creativity must be utilized to develop a suitable model.

One of the major challenges in mapping out a suitable model was to handle the trade-off between ease of use on the one hand and a certain degree of detail in order to map all the different architectural characteristics identified in the interviews into the model. Furthermore, another challenging aspect was the fact that the ten conducted expert interviews represent a relatively small sample size however to some extent mentioned different aspects, which are important in their opinion. This resulted in the fact that the total sum of interviews did not certainly result in a pattern valid for both all companies interviewed in course of this thesis, and also for companies not covered in this set of interviews but hypothetically being users of the model. In order to manage this tradeoff, the first challenge was to define fundamentally how many inputs on the one hand and how many outputs on the other hand should be utilized. As shown in the chapter 5.1 there are various number of potential characteristics describing the design of E/E architectures and similarly different factors to be considered from a strategical, organizational and processual perspective. This raised the question whether all these factors are to be implemented into the model or if just a limited number of factors selected, which would simplify the model significantly.

Again, it must be annotated that the findings of this thesis are based on a relatively small sample size of investigated companies displaying relatively different characteristic which does not allow selecting certain architecture types and discarding others. Due to this reason the decision was made to avoid consolidating the results to superordinate model parameter. By doing so discarding information is prevented at this point and at the same time keep the model flexible and adoptable. The idea of such a multidimensional model is basically to translate the results as presented in chapter 5.1 into a set of criteria describing design and development. In order to meet the requirements regarding visualization and quantifiability, the different parameters are to be expresses by a parallel coordinates graph such as sketched out in Figure 10. The quantitative aspect is hereby given due to the fact that each criterion is expressed on a scale between two bookends.

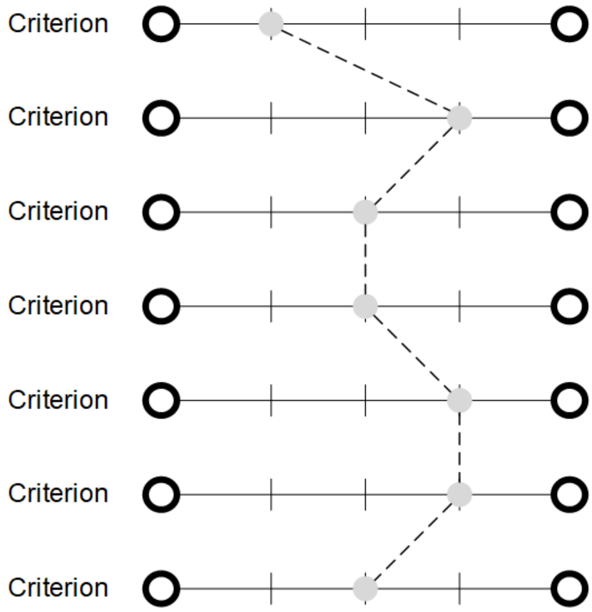

Figure 10: Rough representation of the model outcome representation

However, the actual visualization in form of the parallel coordinates graph does only present the results in a reporting manner by giving an overview over the total set of criteria and does not provide direct information how the different criteria depend on each other. The process of investigating these interdependencies is further presented in the following chapter describing the detailed model formulation process.

6.4. Model Formulation Process

After selecting and appropriate model type the next step is to utilize the empirically gathered insights from the interviews supplemented with the gathered literature based theoretical information to outline the aimed development model out of it. The process of formulating the conceptual model is described in the following. The different steps of the model development process discussed in this chapter are illustrated in Figure 11.

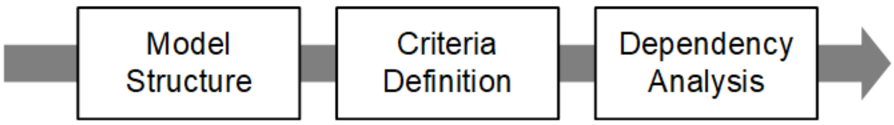

Figure 11: Illustration of the different steps of the model formulation process

6.4.1. Outline Hierarchical Structure

In chapter 5.2.3 the result hypotheses were outlined stating that first the design of future connected E/E architectures is heavily driven by strategy and market aspects on the one hand. Further, the second hypotheses states that chosen architectural design decisions on the other hand influence how companies have to prepare from an organizational and processual perspective in order to development these new type of E/E architectures most effectively. Based on these two hypotheses a sequential model structure is developed with the category E/E architectures as a binding element and core of the model. Sequential model structure means here, that the various criteria derived from the expert interviews are sorted into three categories following the result hypotheses, however without consolidating these different elements into one dimension and thereby losing information. These categories structure the analysis and further provide guidance throughout the usage of the model. Figure 12 displays the three hierarchical levels chosen in the direction of model usage.

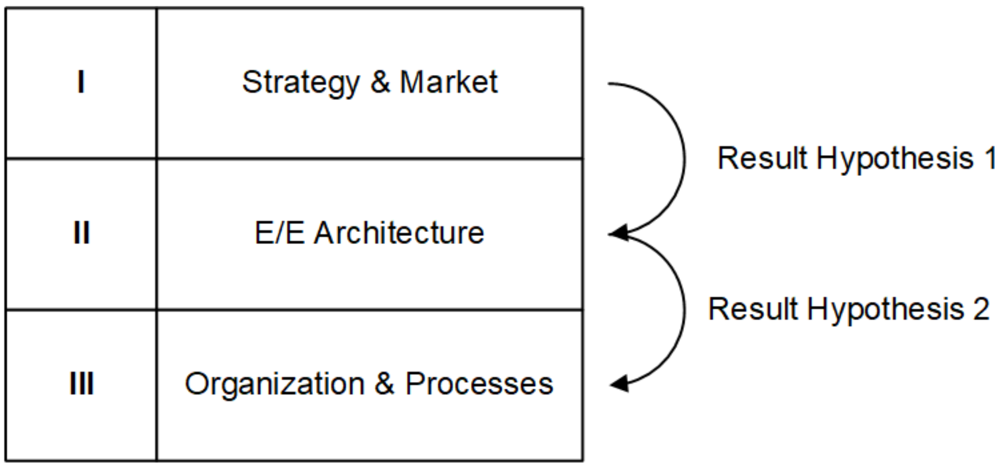

Figure 12: Hierarchical levels of the model

Level I in the model structure consists out of two elements: Strategy and Market. According to the first hypothesis derived from the interviews in chapter 5.1.1 it is claimed that the overall design of E/E architectures is heavily influenced by even these two elements. First, the underlying strategy of the respective IoT product to be developed to and second the market conditions prevailing in the respective company. This category of the model can be seen as the main input parameters influencing the following categories of the model directly or indirectly.

Level II of the model can be seen as the central part connecting everything to each other. Level II consists of different characteristics describing E/E with regards to the architectural focus areas among others described in chapter 5.1.3. This model category has two different purposes. On the one hand the criteria in here can be already seen as output of the model recommending a certain architectural design based on chosen strategy and market conditions and thereby already brings purpose to the users of the model. But on the other hand, the criteria on level II fulfill a second purpose, which is to act as an input to category III mapping organization and processual recommendations on the applied E/E architectures.

Level III in the model structure again covers two different aspects. First the organizational structure of development organizations and second the applied development processes are addressed. Thereby, this last step delivers the second set of output parameters for development organization helping them aligning future product architectures of their future E/E systems to organizational and processual architectures.

6.4.2. Criteria Definition

The next step after outlining the general structure of the model is to define the different criteria and sorting them to the respective model levels and corresponding sub-categories. These represent in the development process the distinct common characteristics exhibited in the design and development process, which aim as a basis for model development as outlined by Gonnet et al. (2007) and discussed in Chapter 6.1. In the following it is described how the criteria to be used in the development model were defined for each respective model level.

The set of chosen criteria assigned to model level I is shown in Table 5. Level I consists according to result hypothesis 1 out of the two subcategories strategy and market heavily influencing the architectural definition process. The criteria in this category were derived mainly from two different sources, namely literature and interviews. In general, it can be said that especial the section 2 in the interviews (see Appendix 1) consisting out of questions trying to grasp what influence megatrends such as connectivity and digitalization have on the interviewee's company product portfolio and what main driver for specific development activities. As mentioned in chapter 5.1.1 many of the interviewees mentioned that the decision to start developing more connected product architectures were based on certain market pulls or highly strategic decisions. These activities are covered in level I. Furthermore, an important source for this model level and especially the subcategory strategy was the set of strategy implications in case companies move towards more connected products discussed by Porter and Heppelmann (2014).

Table 5: Overview criteria model level I

I	Strategy	Startegy Time Horizon
		Make-buy-Strategy
		Service Strategy
		Implementation pace strategy
	Market	Customer Type
		Development depth
		Company importance
		Customer variety
		Regulation
		Reliability Requirements
		Cybersecurity Requirements
		Privacy Requirements

Level II consists out of criteria describing the design of E/E architectures. Referring to the foundations of product architecture such as discussed in chapter 3 the criteria to be defined describing future connected E/E architectures rather refer to architectural characteristics than actual architectural elements. Rather abstract architectural elements are however represented by the defined architectural focus areas such as defined in 5.1.3. Based on the interview results the different architectural characteristics were derived and grouped to the different sub-categories. Especially in section 4 of the interview (see Appendix 1) addressing solutions for design challenges in combination with the literature-based insight from Chapter 3 and 4 such as the quality attributes for IoT systems as outline by Rahman et al. (2018) enabled the derivation of the criteria on this level of the model. The set of chosen criteria assigned to model level II is shown in Table 6.

Table 6: Overview model criteria level II

II	Product Definiton	System Openness
		Architectural Focus
	HW	Modularity in use
		Modularity in design
		Additional capacity
	System SW	Upgradebility type
		In-use scalability
	Signal Layer	Standardization
		Definition Clearity
		Flexibility
		Security
		Compatibility
	Connectivity Layer	Data diretion
		Frequency of connection
		Connection type
		Data Storage Capability

The last model level III can be related to result hypothesis defining organization and processual requirements for company applying more connected E/E architectures. Thus, this level consists of two subcategories namely organization and processes. The selection of these criteria is mainly derived from the conducted interviews, whereas especially section 5 (see Appendix 1) focusing on solutions for challenges in the development process and section 6 focusing on key success factors for successful development of connected products. The set of chosen criteria assigned to model level I is shown in Table 7.

Table 7: Overview criteria model level III

III	Organization	Agility
		Modularity
		Rsik Taking Ability
	Processes	Virtual Testing
		External Collaboration
		Ecosytem Thinking
		Lifetime Responsibility
		Long-Term Thinking
		Complexity Management

After definition of a set of suitable criteria it is important to recall the requirement concerning quantifiability of the model as outlined in Chapter 6.2. As mentioned in 6.3 the usage of a parallel coordinates graph enables to quantify each criterion on a scale between two bookends. These bookends can however be defined in two different ways. Either in a purely quantitative manner or in qualitative manner. A purely quantitative rating in this case would mean rating the respective criteria on a scale from “low” to “high”, which is for example the case for the criterion “customer variety”. Enabling a quantifiable rating in a qualitative manner in contrast would mean rating the respective criterion between to contrasting bookends. A rating of that kind would for example be the case for the criterion “service strategy” which does not enable to be rated as “low” or “high”. In this case, choosing two contrasting bookends is more suitable. In this case the two contrasting bookends “product focused” and “service focused” are defined. A stepped rating now enables to rate a company’s strategy as fully product focused or fully service focused in its extremes but also as something in between having both product and service-oriented elements in its strategical direction.

6.4.3. Interdependence Analysis

The fundamental idea of the model to be developed is to utilize interdependencies on the three hierarchical levels derived from different interviews and thereby first guide companies in their E/E design and development. Thus, in the next step interdependencies between the defined criteria are analyzed.

In order to ensure no information is lost in the during the interdependence analysis considering the fact that 37 different criteria were defined, it was decided to perform the interdependency analysis by utilizing a matrix-based comparison similar to a Design Structure Matrix (DSM). Using such a dependency matrix enabled a structured comparison criterion-by-criterion. Besides the usage as an analytic tool it also acts as a visualization tool of the results. Furthermore, the dependency matrix enabled besides analyzing if there are interdependences between certain criteria to weight them depending on how strong this dependence is.

Besides approaching the analysis in a structured manner some form of scoping to keep the dependency analysis manageable in the limited timeframe of this thesis. Comparing the entire set of 37 defined criteria with each other would result in a total number of 1369 possible combinations to be checked for dependencies. In order to reduce this vast amount of combinations it was reviewed which model levels and corresponding subcategories had to be analyzed for dependencies in order to give value for the actual purpose of the model application. However, in the light of this scoping process it must be annotated that excluding certain combinations from the structured analysis conducted in this thesis, does not mean that it is assumed that in the excluded fields no interrelations are found.

The scoping performed based on the major findings from the interviews summarized into the two results hypotheses because part of the aim of this study is to investigate what factors influence the design and development of connected E/E architectures. Thus, dependency analyzes are only conducted in these fields. As seen in Figure 13 the applied scoping results in the emergence of three areas of dependence analysis which are referred as:

- Architecture definition
- Inter-Architectural Dependencies
- Architecture Development

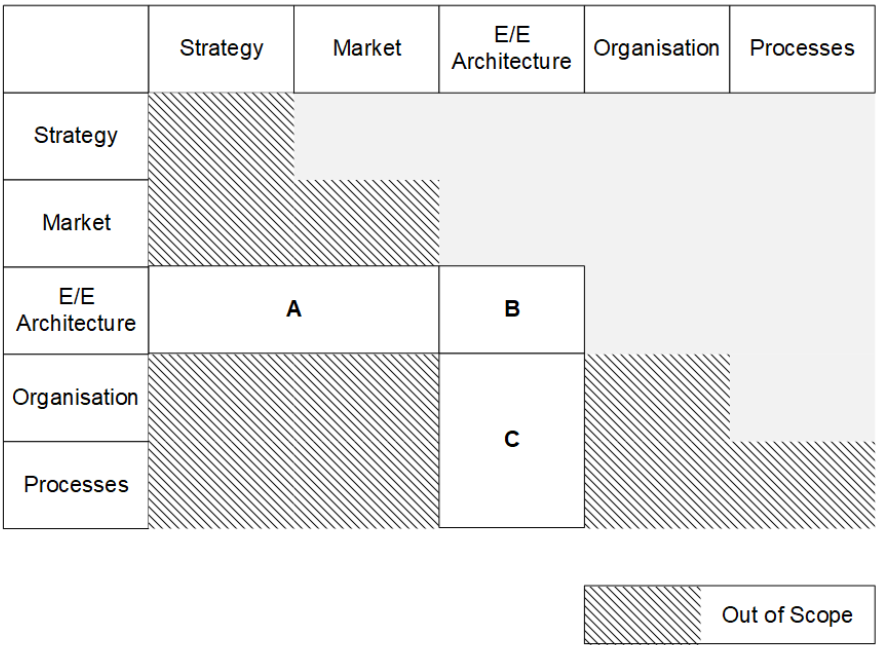

Figure 13: Scope of interdependency analysis utilizing a design structure matrix (Columns impact rows). A: Architecture Definition, B: Inter-Architectural Dependencies, C: Architecture Development

Referring these analysis fields back to the result hypotheses defined in Chapter 5.2.3 it can be said that the analysis of the field "architecture definition" analyzes interdependences corresponding to result hypothesis 1 between level I and II, whereas the field indicated as "Architecture Development Requirements" formally evaluates connection between level II and III accordingly to result hypotheses 2. The third field "Inter-Architectural Dependencies" aims to investigate how the criteria with regards to the E/E architecture are dependent on each other.

The matrix-based interdependency analysis is conducted in a two stepped approach. In the first step information from the interviews is transferred into the matrix for each possible criterion by simply checking whether any interdependence between a pair of criteria can be exhibited. This can be either based on the conducted expert interviews or on the reviewed literature dealing with similar topics. After this initial qualitative dependency analysis in the next step a rating on the previously identified correlating criteria was applied expressing how strong the effect of one criterion on the other one is enabling a more elaborated picture of the interdependence analysis.

Appendix 3 shows the results of the interdependence analysis in form of the developed dependency matrix after applying a quantitative rating to the different identified correlations.

6.5. Model Application

In order to get feedback regarding the fact to which extent the so far developed model fulfils its intended purpose of guiding design and development of connected E/E architectures it is applied on a notional case. Thereby, a third person representing company 2 is consulted being capable of giving objective feedback on the model's validity and appropriateness. In detail the following aspects are aimed to be assed throughout the application case:

- Logics of the model

- Usability
- Value of recommendations

Further, in course of this application it cannot be validated to what extent the recommendations regarding E/E architecture design and development are universally valid for the industry.

The following chapter describes first the case the model was applied on including the setup of the case example and second what insights were gained from this application case.

6.5.1. Application Case

The utilized case to apply the model on is a highly idealized case developed for this specific purpose. Due to time limitations and the fact that the model application process would take considerable amount of time no suitable real case could be found for application of the model. However, in order to get some objective feedback from an external party it was tried to add to some extent real elements to the case.

When modeling a case to apply the model on it was important to choose a situation as realistic as possible, in which the model can provide value. Thus, the starting point of the company in the case should be in a situation were no connected products are developed yet. Further, company 2 interviewed in course of the industry study was chosen as an example. Choosing company 2 in the case provides the advantage that one of the consultants currently working at 3DSE Management Consultants previously had a management position at company 2 and was thereby able to provide realistic inputs during the application process, acting as a user of the model. Considering the fact that company 2 has not developed connected products yet the application case was mapped out as follows:

> *"Company 2 has decided to move towards a more connected product concept. They are a worldwide operating OEM for products in the transportation sector. After screening potential applications and customer needs, they have decided that the most demanded connectivity-based functionality concerns the improvement of their maintenance services. Thus, they decided to connect their currently applied monitoring system to a cloud platform, enabling their customers remote monitoring of their products. Since they have no experience in developing a cloud platform and this does not directly touch upon their core competences, company 2 further decided to utilize an external IoT platform provider."*

Based on this description and the inputs regarding strategy and market conditions for company 2 gained from the company representative (from now on referred to as "user") the application was performed utilizing the DSM expressing the interdependences of the respective criteria. Further, was the application performed in a moderated manner, providing the user with the necessary information regarding the model and how to use it, but also make suggestions once certain aspects were not clear.

6.5.2. Application Results

In general, it can be said that by utilizing the results gained from the structured interdependence analysis it was possible to map recommendations for E/E architecture design and development into the parallel coordinates graph. The results are shown in Appendix 4. Moreover, the application case delivered insights regarding logics, usability and value of the model.

Logics

One issue regarding logics of the model occurring during application that the application of the two result hypotheses, seemed to be differently appropriate. The user experienced it fairly easy to translate strategy and market conditions into different architectural aspects applying interdependencies resulting from hypothesis 1. However, the mapping of design aspects to organizational and processual design aspects according to hypothesis 2 was evaluated as less intuitive. The user commented that limiting processual and organizational development recommendations only to this correlation, might not deliver appropriate results since strategy and development cannot be fully separated as it was done in in applied scoping process. Further, he stated that simplification regarding one-to-one mapping of certain criteria should be treated with caution since in many cases the specific use case has to be considered. In the application it further became clear that the characteristics concerning the network layer cannot be expressed in the same manner as other architectural areas, since this mostly depended from the use case.

Usability

During the application process the DSM showed to be a rather inappropriate tool for usage in the actual model application. It could simply be said, that without moderation the user would have not been possible to apply the model. This was for example due to the fact, that the current representation does not express in a transparent way how the criteria's bookends interact with each other. The current representation only shows, where interrelations can be found and how strong the respective interaction is. The information regarding how the bookends interact with each other was given in an additional document in a written form. Thus, it is concluded that more intuitively accessible information is required. Further insights were gained regarding the level of automation of the model. In general, it was experienced by both the moderator and the user that applying the model is yet associated with certain degree of effort. This means that instead of providing a defined output for a certain input, the model at its current state rather facilitates the discussion by indicating what interrelations are possible. This makes the process rather time-consuming as observed during application. It was however suggested that these issues concerning usability could be solved by presenting the information in a more appropriate way.

Value

After performing the application case the user was asked how he would evaluate the value of the recommendations made in this model. He commented, that especially for the E/E architecture design, the model delivers a basic understanding, in which direction the architecture is heading. Especially from a management point of view it provides a holistic view regarding what strategy and market aspects are affecting the architecture. Already the awareness of this rather basic correlation can help managers, in evaluating what is important and where potential leverage points are. Further it was mentioned that even for companies already developing connected products it might give valuable in order to analyze if there are certain areas where the chosen architecture does align with prevailing strategy and market aspects. However, he further stated, that it will be challenging to derive technical recommendation from these rather abstract characteristics.

6.6. Model Refinement

In the last step of the model development process the insights gained from the basic application case are utilized to improve the model. This refinement, however concerns only the usability of the model, since this is the only aspects which could be assessed in the application case with certainty due to the fact that applied case was highly idealized. No validation of for example the identified dependencies could be performed, which results in the fact that no refinement with regards to this aspect is performed at this point.

The application case of the model clearly showed that the DSM utilized as a whole is rather inappropriate for the usage as tool to guide the decision-making process, since it does not provide all necessary information to fully understand the relation between the different criteria. Moreover, adding the necessary information which respective bookends of a pair of interdependent criteria are connected, would result in further information overload of the DSM. Thus, it was decided that this dependency information is expressed separately in order to improve the model's overall usability.

A better representation of the identified correlations between different criteria was achieved by formulating a set of so called "dependence profiles", outlining for each criterion the main criteria influencing it. These separate profiles enable expressing the identified effects of the criteria on each other in more detail and thereby provide the user with necessary information rather than just stating that there can be found correlations. A template showing how these profiles are set up is shown in Figure 14. The entire set of formulated interdependence profiles can be found in Appendix 5

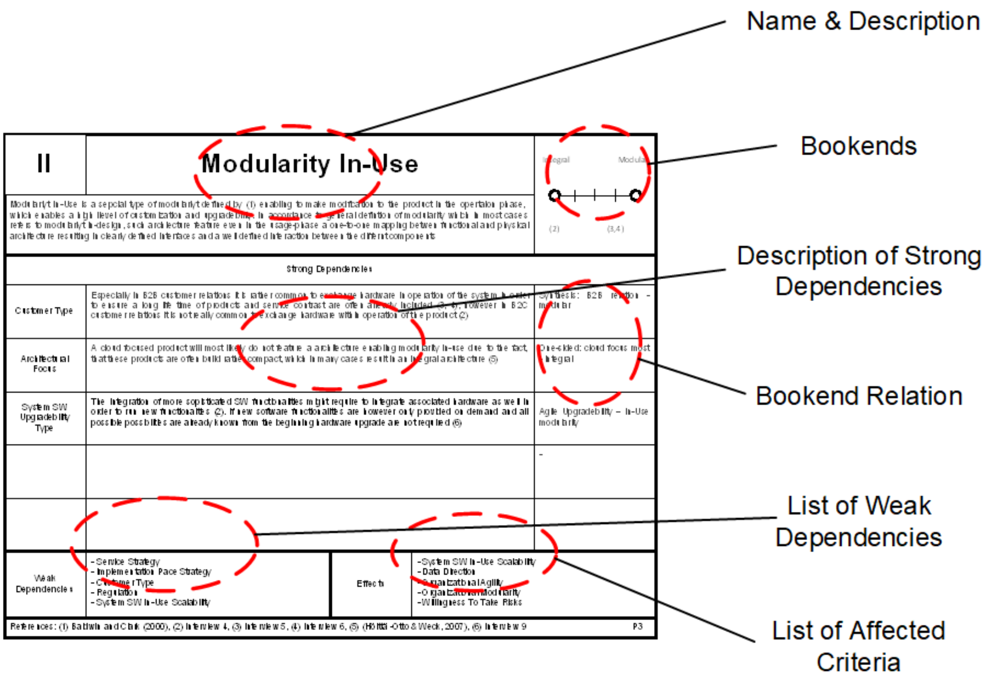

Figure 14: Template of the developed dependence profiles including explanation of the specific information, which can be found

The developed dependence profiles provide basically four different kinds of information. First a description of the respective criterion can be found. Second, it is stated what bookends are assigned to the criterion enabling a quantitative rating. Further, examples are given illustrating where the different interviewed companies can be found on this spectrum. The most important information given in each formulated dependence profile is outlined in the sections "strong dependencies". Here, the criteria strongly impacting (weighted with 3 in the interdependence analysis) the respective criterion are listed including a description of the correlation. This information is further complemented by staining in what way the respective bookends correlate with each other. Lastly, two more lists are included in the dependence profile. The first states "weak dependences" (weighted with 1 or 2 in the interdependence analysis) and the second states those criteria, which are affected by the respective criterion represented in the profile.

6.7. Key Parameters

Besides examining the interaction of the defined criteria in particular, it is further of high interest to analyze, if there are criteria, which are particularly important for designing and developing connected E/E architectures. This analysis is performed by utilizing the so called active and passive sum as discussed in Chapter 6.1.

6.7.1. Key Parameters Architecture Definition

Table 8 shows the active sum of the criteria out of model level I concerning prevailing market and strategy aspects. The given values thereby regard to the analysis referred as architecture definition in Chapter 6.4.3 and is consequently based on result hypothesis 1 stating that the design of connected E/E architectures is influenced by prevailing strategy and market aspects. The values are arranged in descending order.

Table 8: Interdependence characteristics referring to architecture definition process

Label	Criterion	Active Sum
M5	Regulation	20
S3	Service Strategy	16
S2	Make-or-Buy Strategy	15
M7	Cybersecurity Requirements	14
S4	Implementation Pace Strategy	13
M3	Company Importance	12
M8	Privacy Requirements	12
M4	Customer Variety	10
S1	Startegy Time Horizon	9
M1	Customer Type	7
M6	Reliability Requirements	7
M2	Development Depth	6

In general, it can be seen that the active sum varies considerably in the range from 6 – 20. A small active sum however, does not necessarily mean that the respective criterion is unimportant for the architectural definition. It does basically only mean that this criterion has impact only on a small number of other criteria. Nevertheless, it might be the case that those few criteria affected are of high importance in a specific case. However, for companies moving towards more connected E/E architectures it is still especially interesting to know which strategic choices or prevalent market conditions have an impact on several different architectural characteristic, which is shown by a high active sum. Being aware that these criteria have a particularly big impact on the way connected E/E architectures are designed helps R&D organizations to focus on these key criteria in order to have maximum control over the architectural design. If they purposely want to influence the architectural design these are the factors that have to be monitored closely. In this case especially the following three criteria can be pointed out as key levers with regards to the architectural design of future E/E architectures:

- Market Regulations
- Service Strategy
- Make-or-Buy Strategy

6.7.2. Key Parameters Architecture Development

Similarly, to the analysis previously done aiming to identify the key parameters for the definition of connected E/E architectures, the same procedure can be utilized to examine how companies have to address challenges associated with moving towards more connected architectures from an organizational and processual perspective. Table 9 shows the passive sum of the criteria out of model level III concerning organizational and processual aspects. The given values thereby regard to the analysis referred as architecture development in Chapter 6.4.3 and is consequently based on result hypothesis 2 stating that the development organization and processes have to align with the chosen E/E architecture.

Table 9: Interdependence characteristics referring to architecture development

Label	Criterion	Pasive Sum
PR5	Longterm Thinking	21
PR4	Lifetime Responsibility	19
O3	Modularity	16
O4	Risk Taking Ability	16
PR6	ComplexityManagement	15
O2	Agility	13
PR1	Virtual Testing	13
PR3	Ecosytem Thinking	11
PR2	External Collaboration	10

Understanding what the key parameters are from the organizational and processual criteria for developing future connected E/E architectures was identified by utilizing the passive sum. Meaning, that those organizational and processual aspect are especially impacted by the development the chosen architectural design. Thus, in order to ensure that the chosen architecture and the development organization and processes are aligned, companies should be flexible in adopting these parameters. Two processual parameters can be pointed out mostly impacted by architectural choices. These are:

- Lifetime responsibility
- Long-term thinking

7. Critical Reflection

Due to the rather theoretical and technically abstract nature of the research conducted in course of this thesis it was in all phases of the project necessary to make assumptions and utilize hypotheses progress further. In order to assess the validity and quality of the conclusions to be drawn out of the results it is however important to reflect critically on these methodological choices in terms of how they affected the results. This critical reflection is done in the following chapter for the literature study, the industry study and the model development process respectively.

7.1. Literature Study

A major issue when working with product architectures and corresponding architectural descriptions concerns the fact what level of abstraction is applied to be capable delivering value for the respective case. This was also the case in this thesis. This issue affected especially the literature study conducted to build a general understanding of the E/E architecture term and the derived reference architecture. Furthermore, this derived reference architecture was used in the subsequent industry study and model development process. This means, the abstraction issue in fact did influence the entire thesis' pathway fundamentally. By utilizing the reference architecture derived in Chapter 4.2.2 actually the maximum level of abstraction possible was applied. Thus, it is crucial to reflect at this point upon the fact how choosing this architectural description of E/E systems affected the results of this thesis.

The reference architecture was among others used as a facilitating tool within the industry study and the subsequent model developing process. It provided a common ground when communicating with the industry experts referring to fundamentally different products. Furthermore, it facilitated processing the raw data by assigning them on different layers. In fact, the reference architecture turned out to be highly useful in the empirical study, especially since most of the aspect mentioned could be interpreted on a similarly high abstraction level, too. Further, several architectural characteristics could be assigned to the different layers in later phases of the research even on this high abstraction level. Moreover, it turned out to be beneficial considering the fact that also the roles and fields of expertise of the different interviewees varied. The high abstraction level reference architecture proofed to be rather generic for the different fields of expertise.

7.2. Industry Study

As a source of data to examine how future E/E architectures are designed and developed a set of interviews with experts from R&D organizations already developing products with connected functionalities was chosen. Since such an empirical data collection process delivers rather unique results and is barely reproducible, it is important to reflect on first the actual process of data collection and second on the validity of the results gained from this data collection process.

A crucial aspect in terms of how the interviews were conducted regards to the fact that only a rather small number of interviews was conducted. Further, from 10 companies actually only 7 different companies could be utilized to derive conclusions regarding future E/E architectures' design and development. This certainly has to be reflected upon critically.

The aim of thesis study defined int the beginning was approached right from the start in a rather explorative way. Thus, also the conducted empirical study was approached in a rather explorative manner consisting out of a small number of interviews. However, these interviews were relatively long and touched upon several topics associated with future connected E/E architectures in one session. This resulted in a high amount of data, however differing in some parts significantly. The deviation of results was certainly expected early in the research since several different industries and correspondingly varying applications of connectivity were considered. However, the results varied more than initially expected. This resulted in the fact that instead of deriving certain archetypes summarizing all different examined E/E architectures, two result hypotheses were derived enabling to process the empirical data on a higher level of abstraction.

But not only the small sample size is a crucial point to reflect upon but also the sample itself meaning which interview partners were chosen. This can be a crucial aspect affecting the outcome of the interviews and consequently the results' validity, too. As indicated in Chapter 5.1 the person interviewed had very different fields of expertise within their organizations. Which field of expertise was interviewed in the respective companies could not have been directly controlled in this research due to the availability of the interviewees and further due to the fact that the potential interviewees were sourced from the existing customer pool of 3DSE Management Consultants. An ideal study setup would have been certainly to interview different experts within one company. However, in the limited time frame and due to the explorative research approach, such a study setup could not be realized How this variation of fields of expertise affects the results outcome was not considered in course of the analysis of the results directly. However, such variations certainly do affect the results for example in terms of the question regarding key challenges in E/E architectures design. Such information bias was not observed within this study, what however does not mean that it was not present. The different products the interviewees were referring to were basically so different in the way they are designed and developed that it was not possible to judge with absolute certainty if the differences in the architectural design and areas of importance were simple due to varying applications of connectivity or resulted from a bias based on the respective field of expertise. In order to make such deviations visible a significantly bigger sample size is required.

7.3. Model Development

The third part of this thesis was utilizing the empirically gathered data from the to build a conceptual decision model. This model development process was especially associated with several methodological choices affecting the model's pathway fundamentally. The model hereby can be seen as structured way to analyze and process the large amount of data gained from the interviews and make it accessible to research to be conducted in the future. However, in order to be the basis for future research and application it is crucial to critically reflect upon the fact how the model was developed. Further is has to be questioned if it fulfills its initially defined purpose and how it can be used in its current form. Since the model development process is clearly linked to the empirical industry study many of the methodological choices made in this phase of the research are linked to aspects already discussed in previous chapter, too.

As outlined in Chapter 6.3 a major issue at the beginning of the model development process was the selection of a model type suitable to express the varying design and development approaches mapped out throughout the expert interviews. The challenges encountered in this phase of the model development process resulted mainly from dealing with the tradeoff between the defined model requirement regarding usability on the one hand and minimizing the loss of information by consolidating the gained data into few parameters. By choosing a parallel coordinates graph as means of representing the results, the aspect of minimizing loss of information was clearly favored over simplified usability. The overall model structure based on the two derived result hypotheses did already represent a crucial assumption affecting the model's development process' pathway by limiting the impacts on E/E architecture design and development processes to two hypothetical correlations. Building the model on this rather strong assumption as a basis led to the fact that it was assessed inappropriate to apply even more assumption on the model. Again, this inappropriateness was mainly due to large variety of results relative the rather small sample size. By utilizing a parallel coordinate plot the overall structure is in fact depended on two analytically derived hypotheses not being validated. However, the correlations expressed in the interdependence analysis are on the other hand based on observations. They neither affect the model's overall structure nor its scalability, which expresses the power of the developed model. It does give guidance in form of presenting how different companies address certain challenges with regards to design and development of future-proof connected E/E architectures and enables adding data and further insights throughout the time once more knowledge is gained. Thus, the capability of the model to answer challenging design and development aspects will even enhance over time as long as newly gained insights are constantly added to the model.

At the end of the industry study two results hypotheses were derived. However, it appeared that these two hypotheses are differently suitable to be applied in the model Result hypothesis 1 seemed to be rather applicable to explain differences in E/E architecture design given the combined set of influencing criteria from strategy and market on the one side and dependent architectural design criteria on the other side. Several, different design dependencies were directly derived from the interviews and during the application case these correlations were assessed as rather intuitive. Result Hypothesis 2 in contrast appeared not to be that applicable to properly explain why certain development approaches are chosen by the different companies. Two aspects might be potential reasons for this inappropriateness. The first issue when filling out the model for the development requirements was clearly the fact that it is hard to decide upon organizational and processual requirements only based on architectural characteristics. However, due to the scoping applied no other dependencies were analyzed such as the influence of strategy on the processes and organizations. Furthermore, the criteria defined on model development III are rather specific organizational or processual measures. Considering the fact that the architecture was applied on a fairly abstract level it can be assumed that utilizing more abstract organizational and processual criteria as well would have been more appropriate.

After reflection upon theses methodological choices the questions must be raised whether the developed model does fulfill its initially defined purpose as a decision model guiding design and development. And indeed, the model is not fully automated in the way that only a set of inputs are required, which then delivers directly answers how to design E/E architectures and address the development organizationally and processually. Rather users of the model do have to work their way through the model by utilizing the developed set of dependence profiles and reflecting upon the fact if the dependencies outlined are valid for their very own case. Further, the input to be used at the beginning of the model requires reflecting on prevailing strategy and market conditions. However, the transparent setup of the model does furthermore enable to apply it in a backwards directed manner. Companies having already made such decisions are capable to map their chosen design and development approach in the parallel coordinate plot and compare this actual state to the theoretical one. By doing so mismatches can be identified for each criterion respectively.

A last aspect to reflect upon with regards to the developed model concerns the application case. Initially it was planned to assess the validity of the model on a real case. However, due to the fact that no suitable real case was available within time frame of the thesis a highly idealized case was used to validate the model. Thus, it was not possible to assess the validity of the recommendations concerning design and development with certainty, because no real third party could give feedback on the outcomes.

8. Conclusions

The research conducted in course of this thesis indicate that the way E/E architectures are to be designed and developed in the future will be even more challenging than ever before due to the impact of increasing connectivity

The theoretical literature-based analysis regarding the impact of increasing connectivity on the structure of E/E architectures showed:

- Increasing connectivity will significantly impact the way E/E architectures are structured. Due to the high importance of data transmission a new functional layer will emerge. The newly emerging signal layer will significantly add up to the already existing complexity of the system layer

Further, the conducted interviews with experts already developing connected product system across different industries displayed:

- There certainly is no silver bullet approach for designing and developing future connected E/E architectures, since as the industries and applications differ significantly so do the architectural design and development approaches.
- The different technical and functional layers, which can be exhibited show notably different architectural characteristics and especially with regards to the signal layer many different architectural decisions have to be made.

Lastly, by trying to develop a conceptual decision model aiming to guide design and development decisions it was indicated:

- Decisions regarding architectural design and development of connected E/E architectures across industries cannot be broken down in highly simplified models valid for different industries
- The outlined comprehensive model developed on the basis of two hypotheses provides guidance for companies aiming for more connected products. Especially the impact of strategy and market aspects on architectural design decisions indicated to deliver valuable insights

The conclusion drawn out of the literature study and the industry study display the great challenges in terms of designing and developing future connected E/E architectures. Whereas E/E architectures get increasingly complex, design and development approaches are drifting more and more apart. This impressively shows the necessity for guiding companies in their transformational process towards a connected product system. This thesis builds the base for providing such guidance, however future work has to elaborate on these findings in order to provide even more value.

9. Outlook

The insights gained from this rather explorative research build the foundation to give a basic understanding where future E/E architectures are heading to in the light of increasing connectivity. However, in order to elaborate on this foundation, further research in this field is required in order to provide further value to companies moving towards a more connected product portfolio. In the following some recommendations are made with regards to future work suggested to be done in this field.

The first recommended step is to conduct a more elaborated validation of the results of this research in comparison to the idealized application performed in course of this thesis. Further, this validation should concern several parts of this thesis considering the fact different assumption and conclusions were made throughout the entire research. Before trying to validate the derived model, the result hypotheses should be validated concerning both the architecture definition process and the architecture development requirements. This can for example be done by explicitly asking companies such as those interviewed in course of this thesis if they experienced the two hypotheses come to play. After validation of these fundamental relations the derived model including the different interrelations summarized in the respective dependence profiles can be checked for validity. An appropriate process of doing so would be to find companies, which have initiated development of connected products already and use the criteria from model level I concerning strategy and market aspects as an input and fill out the rest of the criteria on level II concerning product architecture and level III concerning processual and organizational requirements. This would show which of the outlined dependencies are universally valid on the one hand and where information is still required to make proper recommendations for E/E architecture design and development.

The next step should be scaling the model and to a more comprehensive state. The derived model and interdependencies did not claim to be exhaustive from the first place due to the explorative nature of this thesis and in the end, the model certainly did not cover all aspects of E/E architecture design and development. However, in a more comprehensive study This would also enable to conduct a more appropriate sampling. This would ensure that the results of the study are biased by a certain field of expertise. Having a more comprehensive data set however does not necessarily mean that the model gets more complex. Having a larger set of data also enable to consolidate the data further without losing too much information.

The last point, which future work in this research field might concern is deriving more technical details, which was out of scope for this thesis in the first place. Shifting the level of architectural abstraction applied in this thesis to a more technical architecture would facilitate users of the model also in making technical decisions.

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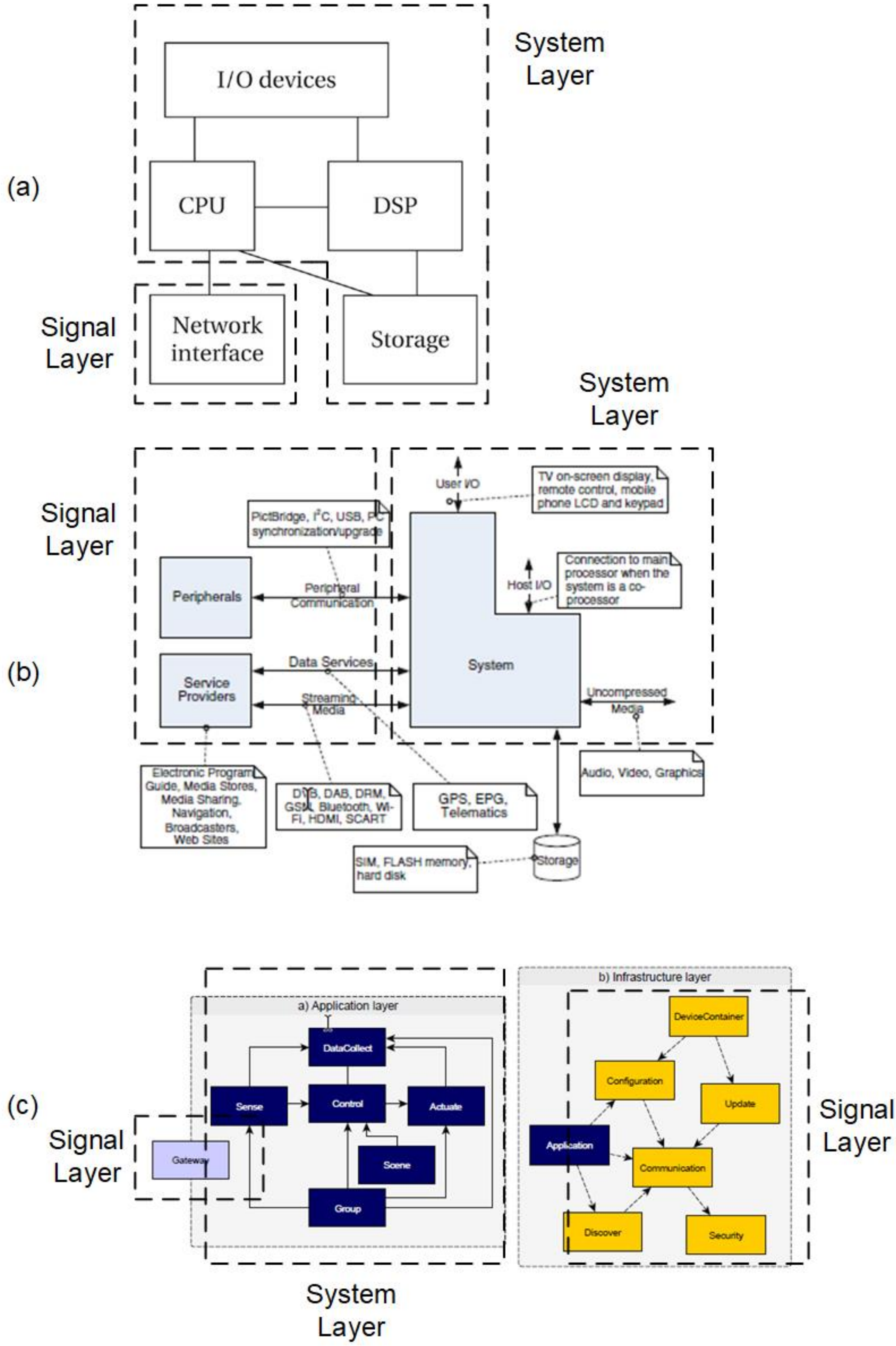
11. Appendix

Appendix 1: Interview guideline used throughout the interviews with the industry experts:

	1. Project information and background - Background and delimitations
	2. Influence of IoT and digitalization - Which meaning do have the topics digitalization, IoT, connectivity and cloud computing for your products? - Did you already conduct projects/develop products? - What were the main drivers/hurdles for initiating developing activities?
Open question	**3. Challenges** - Which challenges do emerge for future E/E architectures with regards to o Design o Development
	4. Solutions - Challenges with regards to design o Which components or architectural elements will be more important in future architectures? o How can the functionality over the entire lifecycle be assured? o How to ensure future-proof architectures especially with regards to extendibility and upgradability? - Challenges with regards to development o What organizational or processual challenges were associated with the development of connected products? o Are the functionalities implemented step by step? o Can established development routines be utilized for such new products? o Do development cycles decrease in such products? Release of unfinished products and update over the air? o What do Make-or-buy decisions depend on? Own development or platform provider?

	○ Concurrent engineering or „waterfall“? ○ Do new stakeholders have to be involved in the development and how can a successful cooperation be ensured?
If implementa-tion was already successful If implementa-tion was not per-formed yet	**5. Key success factors** - Based on your previous experience, what do you think are key success factors for implementing connected and digital products? **OR** - What does have to change strategically, organizationally and culturally within the or-ganization in order to implement IoT based successfully?

Appendix 2: Different functional descriptions utilized to describe the functional architecture of consumer electronics. Dotted lines were added in order to map out the functional system layer and signal layer (a) Functional block diagram to describe the hardware structure of a typical device (Wolf, 2012) (b) Context diagram to describe the structure of generic consumers electronic products (Trew et al., 2011). (c) Functional decomposition of a connected lighting system (Mathews et al., 2017).



Appendix 3: Results of the interdependency analysis utilizing a weighting-based DSM (Columns impact rows)

III									II																		
ComplexityManagement	Longterm Thinking	Lifetime Responsibility	Ecosytem Thinking	External Collaboration	Virtual Testing	Risk Taking Ability	Modularity	Agility	Data Storage Capability	Connection Type	Frequency of Connection	Data Diretion	Compatibility	Security	Flexibility	Definition Clearity	Standardization	In-Use Scalability	Upgradeability Type	Additional Capacity	Modularity In-Design	Modularity In-Use	Architectural Focus	System Openness			
PR6	PR5	PR4	PR3	PR2	PR1	O4	O3	O2	P16	P15	P14	P13	P12	P11	P10	P9	P8	P7	P6	P5	P4	P3	P2	P1			
									-	-	-	1	-	-	-	-	1	-	-	2	3	2	-	-	S1	Startegy Time Hprizon	I
									-	-	-	-	1	1	-	3	3	1	-	-	2	-	2	2	S2	Make-or-Buy Strategy	
									-	-	3	2	2	-	-	-	-	1	2	-	-	2	3	1	S3	Service Strategy	
									-	-	-	2	-	-	-	-	-	2	2	2	3	2	-	-	S4	Implementation Pace Strategy	
									-	-	-	-	-	1	1	-	1	-	1	-	-	3	-	-	M1	Customer Type	
									-	-	-	-	-	1	-	-	1	-	-	-	2	2	-	-	M2	Development Depth	
									-	-	-	-	-	-	3	-	3	-	-	-	3	-	-	3	M3	Company Importance	
									-	-	-	1	-	-	3	1	2	-	-	-	2	-	-	1	M4	Customer Variety	
									-	-	-	3	-	3	-	-	-	3	3	-	-	2	3	3	M5	Regulation	
									-	-	-	-	-	1	-	-	-	-	-	-	-	2	3	1	M6	Reliability Requirements	
									1	-	-	3	2	3	-	-	-	-	-	-	-	-	3	2	M7	Cybersecurity Requirements	
									1	-	-	1	2	3	-	-	-	-	-	-	-	-	3	2	M8	Privacy Requirements	
3	-	2	3	2	-	2	2	1	-	-	-	-	3	2	2	3	3	2	2	1	-	-	-	X	P1	System Openness	II
-	2	2	2	2	-	2	-	-	2	3	3	2	1	1	-	-	-	2	2	-	2	3	X	-	P2	Architectural Focus	
-	3	2	-	-	-	2	3	2	-	1	-	2	-	-	-	-	-	2	3	3	1	X	-	-	P3	Modularity In-Use	
-	3	-	-	3	-	3	3	2	-	-	-	2	-	-	-	-	-	-	-	-	X	1	-	-	P4	Modularity In-Design	
-	3	1	-	-	-	2	-	2	-	-	-	-	1	-	-	-	-	2	3	X	-	-	-	-	P5	Additional Capacity	
3	2	2	-	-	2	-	2	3	-	-	-	-	1	-	-	-	-	2	X	3	-	3	2	2	P6	Upgradebility Type	
1	2	3	-	-	2	-	2	3	-	-	-	1	-	-	-	-	-	X	2	3	-	2	2	2	P7	In-Use Scalability	
2	2	2	3	-	2	2	2	-	-	-	-	-	2	1	2	3	X	-	-	-	-	-	-	-	P8	Standardization	
2	-	-	-	-	2	-	2	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	P9	Definition Clearity	
1	-	-	-	-	2	2	-	-	-	-	-	-	2	-	X	-	2	-	-	-	-	-	-	-	P10	Flexibility	
-	1	3	-	-	-	-	-	-	-	1	-	2	2	X	-	-	1	-	-	-	-	-	-	-	P11	Security	
3	1	2	3	-	3	-	-	-	-	-	-	1	X	2	2	-	2	-	1	1	-	-	-	-	P12	Compatibility	
-	2	-	-	-	-	1	-	-	-	1	-	X	1	3	-	-	-	1	-	-	2	2	2	-	P13	Data Diretion	
-	-	-	-	-	-	-	-	-	3	2	X	2	-	-	-	-	-	-	-	-	-	-	2	-	P14	Frequency of Connection	
-	-	-	-	3	-	-	-	-	3	X	2	1	-	1	-	-	-	-	-	-	-	1	-	-	P15	Connection Type	
-	-	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	P16	Data Storage Capability	

Appendix 4: Results of the application case

I	Strategy	Startegy Time Horizon	Short				●		Long
		Make-buy-Strategy	Make				●		Buy
		Service Strategy	Product focused			●			Service focused
		Implementation pace strategy	Step-by-Step	●					All or Nothing
	Market	Customer Type	B2B	●					B2C
		Development depth	low				●		high
		Company importance	low				●		high
		Customer variety	low		●				high
		Regulation	low					●	high
		Reliability Requirements	low					●	high
		Cybersecurity Requirements	low				●		high
		Privacy Requirements	low			●			high
II	Product Definiton	System Openness	Closed	●					Open
		Architectural Focus	Product		●				Cloud
	HW	Modularity in use	Integral				●		Modular
		Modularity in design	Integral				●		Modular
		Additional capacity	None				●		High
	System SW	Upgradebility type	Agile					●	Pre-Defined
		In-use scalability	low	●					high
	Signal Layer	Standardization	Own Interface					●	Industry Standards
		Definition Clearity	low		●				high
		Flexibility	low	●					high
		Security	low				●		high
		Compatibility	low	●					high
	Connectivity Layer	Data diretion	One Directional	●					Two Directional
		Frequency of connection	low	●					high
		Connection type	Local Network					●	Mobile Network
		Data Storage Capability	Yes	●					No
III	Organization	Agility	Waterfall		●				Agile
		Modularity	Integral		●				Modular
		Rsik Taking Ability	low		●				high
	Processes	Virtual Testing	low		●				high
		External Collaboration	low		●				high
		Ecosytem Thinking	low		●				high
		Lifetime Responsibility	low		●				high
		Long-Term Thinking	low		●				high
		Complexity Management	low		●				high

Appendix 5: Dependence profiles

I — Strategy Time Horizon (Strategy)

Short — Long: (1)

Strategy Time Horizon refers to the fact whether a company is planning rather in the short-term or in the long-term. (1) for example is designing their products with a short time horizon and does not consider advantages for next product generations in their current design. Further this might refer to the fact whether already today actions are taken guiding the direction for future improvements of the product such as facilitating future design changes or planning additional capacities into the product

Strong Effects		Weak Effects	
	- Modularity In-Design		- Modularity In-Use - Additional Capacity

References: (1) Interview 1 — S1

I — Make-or-Buy Strategy (Strategy)

Make — Buy: (1) (2)

The Make-or-Buy Strategy characterises whether a company is planning to conduct most of their development activities on their own or if they are willing to collaborate with development partners. Especially in the area of IoT external development partners are utilized for system components such as cloud platforms. When companies stated what their decision regarding make or buy depends on different factors were mentioned. (1) is conducting most of their development activities fully on their own since they consider for example the cloud platform as their product. (2) on the other hand stated that they simply do not have the organizational capabilities for many things.

Strong Effects		Weak Effects	
	- Standardization - Defintion Clearity		- System Openness - Architectural Focus - Modularity In-Design

References: (1) Interview 4, (2) Interview 10 — S2

I — Service Strategy (Strategy)

Product Focused — Service Focused: (1) (2)

The Service Strategy refers to the fact whether technology-based services especially associated with connectivity are seen as a product or if A company still limits themselves to the physical product, which impacts first what development activities are conducted in general and second what development activities are conducted internally. (1) stated that they move only slowly towards more connected product since their strategy is still rather product focused. (2) on the other hand has decided to shift their strategy more towards services in order to keep up with large digital global players such as amazon and google.

Strong Effects		Weak Effects	
	- Architectural Focus - Frequency of Connection		- Modularity In-Use - Upgradeability Type - Compatibility Type - Data Direction

References: (1) Interview 1, (2) Interview 4 — S3

I — Implementation Pace Strategy (Strategy)

Step-by-Step — All or Nothing: (2) (3)

The Implementation Pace Strategy describes a company's approach to implement more connected functions into their products. This can be performed at a different implementation pace ranging from a step-by-step approach slowly scaling from a basic monitoring approach to more sophisticated functions comparably to the IoT maturity model proposed by (1) on the one side, to an approach where the more basic steps are skipped in order to start at a relatively high sophistication level, which was for example followed by (3)

Strong Effects		Weak Effects	
	- Modularity In-Design		- Modularity In-Use - Additional Capacity - Upgradeability Type - In-Use Scalability

References: (1) Porter & Heppelmann, 2014, (2) Interview 1, (3) Interview 4 — S4

I — Customer Type (Market)

B2B — B2C

(1) (2)

The customer type defines whether a business to business (B2B) or a business to consumer (B2C) customer relation is existing. This relation can have impacts on various aspects of the business. (1) for example stated that they their B2B relations enables them to have close contact and communication with their customers. Further, it is often the case that products in a B2B relation are more likely to have service components integrated.

Strong Effects	- Modularity In-Use	Weak Effects	-

References: (1) Interview 8, (2) Interview 4 — M1

I — Development Depth (Market)

Low — High

(1) (2)

Development Depth refers to the amount of product components actually developed in the company. Depending on the product and company A large amount of components can be developed externally and the company selling the actual product rather can be seen as the system integrator. The development depth with regards to product architecture defines for example how much influence a company has on the design of the different components of the system.

Strong Effects		Weak Effects	- Modularity In-Use - Modularity In-Design

References: (1) Interview 1, (2) Interview 5/7 — M2

I — Company Importance (Market)

low — high

(2) (1)

The importance of the company has an effect on several design decisions, since a relatively unimportant company with a small market share cannot dictate any technology specifications to the market. It is rather dependent on technological standards existent on the market. In the light of connectivity this results in the fact that an inimportant company for example cannot decide that it enables connection only to their own products. Rather it has to ensure that it enables connection to product from various different companies and even some of their own competitors. Large companies such as from the automotive area in contrast can define their own standards

Strong Effects	- System Openness - Modularity In-Design - Standardization - Flexibility	Weak Effects	

References: (1) Interview 4, (2) Interview 10 — M3

I — Customer Variety (Market)

low — high

(1)

The variety of customers does in the field of connectivity especially has influence on the fact if flexible interfaces are required or not. Especially if the company's importance is relatively low in comparison to the customers' importance the different customers' needs have to be considered. In order to deal with the increased complexity of very different customer needs companies however have to develop design strategies to keep this complexity manageable. (1) for example stated that they have to connect their product to significantly different customer platforms, what they have to consider in the design of their interfaces.

Strong Effects	- Flexibility	Weak Effects	- Modularity In-Design - Standardization

References: (1) Interview 6 — M4

I Regulation (Market)

Low High

(2) (1)

The fact whether a product or the entire associated industry is heavily regulated especially affects the design of connected E/E architectures in different ways. It might be the case that no components can be exchanged after roll out of the product or that the access to the system must be limited (1).

Strong Effects	- System Openness - Architectural Focus - Upgradeability Type - Security - Data Direction	Weak Effects	- Modularity In-Use

References: (1) Interview 9, (2) Interview 4 M5

I Reliability Requirements (Market)

Low High

(1) (2)

Reliability concerns the fact whether a system or certain functions of the system are required to be running continuously without any service interruption. In the field of IoT this for example has to be considered for decisions regarding location of certain functionalities. If a function has high requirements in terms of reliability, a rather reliable signal transmitting technology must be applied in order to run the function for example on a cloud platform.

Strong Effects	- Architectural Focus	Weak Effects	- Modularity In-Use

References: (1) Interview 4, (2) Interview 9 M6

I Cybersecurity Requirements (Market)

Low High

Cybersecurity Requirements concern the system security against malicious attackers potentially harming certain functions or the entire system's functionality. According to (1) security concerns are one of the biggest barriers for companies to overcome in order to achieve success in the world of IoT

Strong Effects	- Architectural Focus - Security Signal Layer - Frequency of Connection	Weak Effects	- System Openness - Compatibility

References: (1) Ganguli & Friedman, 2017 M7

I Privacy Requirements

Low High

Data Privacy Requirements do in contrast to regulation, reliability and cybersecurity requirements do not concern the actual functionality of a system and rather the protection of sensitive data. This data might concern both sensitive data from the customer's or from the manufacturer's perspective

Strong Effects	- Architectural focus - Security Signal Layer	Weak Effects	- System Openness - Compatibility Signal Layer

References: M8

<table>
<tr><td>II</td><td>System Openness</td><td rowspan="2">Closed Open

(2) (4)</td></tr>
<tr><td colspan="2">Describes the general openness of the system with regards to external development partners. To open systems external development partners can add functionalities or connect their products to the existing product system. By performing a closed system companies can gain maximum benefit from the product system by claim both physical products and associated virtual services for themselves.</td></tr>
<tr><td colspan="3">Strong Dependencies</td></tr>
<tr><td>Company importance</td><td>Only if the company has significant importance in the industry and can dictate how their customers set up their connected systems they are able to offer a rather closed system (1), however if a company is capable of performing a closed system approach they can gain maximum value from the product system as it was seen by (2)</td><td>Low importance – open system</td></tr>
<tr><td>Regulation</td><td>A highly regulated system might not allow any changes in the system from external development partners due to regulations concerning for example the functional safety (3)</td><td>High regulations – closed system</td></tr>
<tr><td></td><td></td><td>-</td></tr>
<tr><td></td><td></td><td>-</td></tr>
<tr><td></td><td></td><td>-</td></tr>
<tr><td>Weak Dependencies</td><td>- Make-or-Buy strategy
- Service Strategy
- Cbersecurity Requirements
- Privacy Requirements
- System SW Upgradebility Type</td><td>Strong Effetcs</td><td>- Signal Layer Standardization
- Signal Layer Definiton Clearity
- Signal Layer Flexibility
- Signal Layer Security
- Signal Layer Compatibility</td></tr>
<tr><td colspan="3">References: (1) Porter & Heppelmann, 2014 (2) Interview 4, (3) Interview 10, (4) Interview 6</td><td>P1</td></tr>
</table>

<table>
<tr><td>II</td><td>Architectural Focus</td><td rowspan="2">Product Cloud

(2) (1) (3)</td></tr>
<tr><td colspan="2">The architectural focus refers to the fact whether the company puts more focus on the combined product-service system enabled by the connectivity. Having the physical product on the one end or a cloud or connected IT-system companies can choose where to place more functionalities of their product. Amazon's Alexa for example is a rather cloud based product since many functionalities are placed in the cloud and mainly executing functions are placed in the actual product</td></tr>
<tr><td colspan="3">Strong Dependencies</td></tr>
<tr><td>Service Strategy</td><td>Due to the fact that most of the companies interviewed were historically hardware focused, moving to more connected systems did not significantly change their focus. Except of (1) no company is planning to move functionalities realized physically before to virtual cloud based functions. (1) had the intention to gain value</td><td>Service focus – cloud focus</td></tr>
<tr><td>Regulation</td><td>High regulations might require always servicing, which in a cloud based product-system is not always given especially if mobile networks are used for crucial functionalities (2)</td><td>High regulations – Product focus, but use-case and data connectio type must be onsidered</td></tr>
<tr><td>Reliability</td><td>High requirements in terms of reliability might require always servicing (4), which in a cloud based product-system is not always given especially if mobile networks are used for crucial functionalities (2)</td><td>High reliability req – Product focus, but use-case and data connection type must be considered</td></tr>
<tr><td>Cybersecurity</td><td>Mainly product-focused architectures are safer because less data is transferred</td><td>High cybersecurity req – Product focus</td></tr>
<tr><td>Privacy</td><td>Mainly product-focused architectures are safer because less data is transferred</td><td>High cybersecurity req – Product focus</td></tr>
<tr><td>Weak Dependencies</td><td>- Make-or-Buy Strategy
- System SW Upgrade Type
- System SW Scaling</td><td>Strong Effects</td><td>- Modularity In-Use
- Modularity In-Design
- Frequency of Connection
- Connection Type</td></tr>
<tr><td colspan="3">References: (1) Interview 4, (2) Interview 10, (3) Amazon.com, (4) Interview 2</td><td>P2</td></tr>
</table>

II	Modularity In-Use (HW)	Integral / Modular: (2) Integral … (3,4) Modular
	Modularity In-Use is a special type of modularity defined by (1) enabling to make modifications to the product in the operation phase, which enables a high level of customization and upgradability. In accordance to the general definition of modularity which in most cases refers to modularity in-design, such architectures feature even in the usage-phase a one-to-one mapping between functional and physical architecture resulting in clearly defined interfaces and a well defined interaction between the different components	
Strong Dependencies		
Customer Type	Especially in B2B customer relations it is rather common to exchange hardware in operation of the system in order to ensure a long life time of products and service contrast are often already included (3, 4), however in B2C customer relations it is not really common to exchange hardware within operation of the product (2)	Synthesis: B2B relation - modular
Architectural Focus	A cloud focused product will most likely do not feature a architecture enabling modularity in-use due to the fact, that these products are often build rather compact, which in many cases result in an integral architecture (5)	One-sided: cloud focus most - integral
System SW Upgradebility Type	The integration of more sophisticated SW functionalities might require to integrate associated hardware as well in order to run new functionalities (2). If new software functionalities are however only provided on demand and all possibilities are already known from the beginning hardware upgrade are not required (6)	Agile Upgradebility – In-Use modularity
		-

Weak Dependencies	- Service Strategy - Implementation Pace Strategy - Customer Type - Regulation - System SW In-Use Scalability	**Strong Effects**	- System SW In-Use Scalability - Data Direction - Organizational Agility - Organizational Modularity - Willingness To Take Risks

References: (1) Baldwin and Clark (2000), (2) Interview 4, (3) Interview 5, (4) Interview 6, (5) (Hölttä-Otto & Weck, 2007), (6) Interview 9 P3

II	Modularity In-Design (HW)	Integral / Modular: (3, 4)
	The way a product's sub-functions are mapped to its physical components characterizes the degree of modularity of an architecture. A one-to-one mapping of functions and physical components and few clearly defined interfaces represent thereby a modular architecture. The opposite is called an integral architecture. Modularity In-Design is meant in most cases when referring to the term modularity. It is especially beneficial in specific R&D issues such as product change and complexity management (1). However, products underlying high technical constraints such as weight or volume often exhibit a more integral architecture minimizing number of components (2)	
Strong Dependencies		
Strategy Time Horizon	Modularity In-Design does in most cases especially pay-off in the long term over several different product derivatives, since then the implications for product development come to play. (3) for example stated that they do not follow a modular product architecture since they do not think about their product development performance in the long-term	Long Term Strategy – Modular Architecture
Implementation Pace Strategy	According to (1) a modular architecture is especially beneficial with regards to product change because a change of a specific component in a modular architecture does affect only a few other components and their interaction is clearly defined. If a company has a clear vision to move towards a more connected architecture, however is only capable to conduct this shift iteratively a modular product architecture is key to facilitate this process (4)	Step by Step Implementation Pace Strategy – Modular Architecture
Company Importance	The field of IoT is currently associated with fast technology driven change and there are for many applications no standards yet. This means especially for smaller companies, who are not able to dictate own specifications, that they have to adapt between different derivates since technology has changed. Sometimes it is even the case that big manufacturer buy the market empty so smaller companies have to change certain components (4)	Low Company Importance – Modular Architecture

Weak Dependencies	- Architectural Focus - Make-or-Buy Strategy - Development Depth - Customer Variety	**Strong Effects**	- Organizational Agility - Organizational Modularity - Risk Taking - Longterm Thinking

References: (1) Ulrich & Eppinger (2012), (2) Hölttä-Otto & Weck (2007), (3) Interview 1, (4) Interview 10 P4

II	**Additional Capacity** (HW)	None High (3) (1)
The fact that future E/E architectures are always connected makes it easier than ever before to implement updates and extension in the actual usage phase. However, in order to enable the integration of larger new software functionalities it might be necessary to utilize hardware, which was not used at the time of roll-out. Additional capacities can be achieved by different means. (1) for example build in specific hardware for functionalities, which are planned to be implemented, but not fully developed during roll-out. (2) on the other hand stated that it must be more general additional capacities such as unused interfaces or additional computing power.		
Strong Dependencies		
Modularity In-Use	Only if architecture enables modularity in-use aditional capacities are required	Modular In-Use Architecture – High Additional Capacities
Upgradeability Type	The upgradeability type defines significantly if additional capacities are required. (3) for example offers only upgrades on demand which are moreover predefined during the rollout of the product. They only activate or deactivate certain functionalities and thereby know already at the beginning what the product will be capable to do. (1) on the other hand implements hardware without knowing with certainty for what they are used for later on	Pre-Defined – No additional Capacities needed
In-Use Scalability	In-Use Scalability is rather comparable to the upgradeability type and defines whether additional capacities are required	High In-Use Scalability – High Additional Capacities

Weak Dependencies	- Strategy Time Horizon - Implementation Pace Strategy - System Openness - Compatibility	**Strong Effects**	- Longterm Thinking
References: (1) Interview 4, (2) Interview 10, (3) Interview 9			P5

II	**Upgradeability Type** (System SW)	Agile Pre-Defined (1) (2)
Connected products enable companies to implement new functionalities to products already on the market with ease through update over the air. However, the upgradeability of the connected product can vary significantly from application to application. Whereas (1) for example is planning to implement new functionalities throughout the entire lifecycle of the product and does not even know what functionalities will be developed, has (2) only a defined set of functionalities from which the users can choose, which only get activated and deactivated		
Strong Dependencies		
Regulations	Some industries are highly regulated since they are for example associated with safety of the users. Such high regulations can affect what sort of upgradeability type is chosen. Highly regulated systems do for example not allow changes of the system throughout usage, which only allows for Pre-Defined Upgrades (2)	High Regulations – Pre-Defined Updates
Modularity-In use	In order to use an agile upgradeability type optimally it is important to enable modularity In-Use or additional capacities	In-Use modular architecture – Agile Upgradeability
Additional Capacities	In order to use an agile upgradeability type optimally it is important to provide additional capacities or modularity In-Use	Additional Capacities – Agile Upgradeability

Weak Dependencies	- Service Strategy - Implementation Pace Strategy - System Openness - Architectural Focus	**Strong Effects**	- Modularity In-Use - Additional Capacity - Organizational Agility - Organizational Modularity
References: (1) Interview 4, (2) Interview 9			P6

II	In-Use Scalability (System SW)	low high (3) (1)
In-Use Scalability enables to reduce product development lead times significantly. Through connectivity product upgrades can be implemented throughout the whole life time. Thus, companies can start with providing basic functionalities at the beginning and then scale them to more sophisticated ones such as done by (1) and (2) . However, not all companies are utilizing it. (4) for example stated that their customers want to know what they are paying for right from the start, which does not allow to deliver only basic functionalities		
Strong Dependencies		
Regulation	Some industries are highly regulated since they are for example associated with safety of the users. Such high regulations can affect what sort of upgradeability type is chosen. Highly regulated systems do for example not allow changes of the system throughout usage, which only allows for Pre-Defined Upgrades (3)	High Regulation – Low In-Use Scalability

Weak Dependencies	- Implementation Pace Strategy - System Openness - Architectural Focus - Modularity In-Use - Additional Capacities	**Strong Effects**	- Additional Capacities - Organizational Agility - Organizational Modularity - Lifetime Responsibility

References: (1) Interview 4, (2) Interview 6, (3) Interview 9, (4) Interview 5 P7

II	Standardization (Signal Layer)	Own Interface Industry Standard (1) (2)
Utilizing standards in the signal layer refers to applying industry wide communication technologies for hardware and software enabling communication with all other units in a network utilizing standards as well. However, it also means being dependent on the respective standard and forced To change in case standards are not state-of-The-art anymore.		
Strong Dependencies		
Make-or-Buy Strategy	Especially Make-or-Buy decisions with regards to digital services such as cloud platforms it might be important to consider utilizing of standards in the signal layer. (3) stated that they utilize standard communication technologies in order to enable facilitated collaboration with external IoT platform providers	High buy-ratio – Industry standards
Company Importance	If the company does not have the necessary importance at the market it is not capable to dictate own standards neither to their customers nor to suppliers. Large automotive companies however can dictate own interface design and their collaboration partners have to adapt to them (2)	Low Company Importance – Industry standards
System Openness	The more open a system is the more it is recommended to utilize industry standards in order to utilize the full potential of an open system approach.	Open system – Industry Standards

Weak Dependencies	- Customer Variety - Signal Layer Flexibilty - Signal Layer Compatibility	**Strong Effects**	- Signal Layer Definition - Signal Layer Flexibility - Signal Layer Compatibility - Organizational Capabilities - Virtual Testing

References: (1) Interview 4, (2) Interview 10, (3) Interview 9 P8

II	Definition Clearity (Signal Layer)	low high (1) (2)
Clearly defined interfaces facilitate connecting different components with each other or collaboration with external partners. Clearly defined means in this case that there are only few interfaces and all information is given to utilize this interface. If the interfaces are clearly defined less communication is required and so-called black-box development can be applied (1)		
Strong Dependencies		
Make-or-Buy Strategy	Especially when working with many external developers a clear definition of the signal layer is required in order to reduce the amount of communication in a development partnership. (2) stated that they were working together with external developers, who have not had any questions throughout the development collaboration due to the clearly defined interfaces	High Buy-Rate – High Definition Clearity
System Openness	In order to fully benefit of an open system clearly defined interfaces are necessary	Open System – High Defintion Clearity
Standardization	Utilizing industry standards usually comes along with clearly defined interfaces, which are easy to work with.	Use of Industry Standards – Clearly Defined Interfaces
Weak Dependencies		**Strong Effects**
References: (1) Baldwin & Clark (2000), (2) Interview 4,		P9

II	Flexibility (Signal Layer)	Low High (1) (2)
Flexibility in terms of the Signal Layer refers to the fact that customers with varying type of system components can connect with ease to the product. This was for example very important for (2) because their customers' systems which they have to connect to vary significantly. In order to avoid developing a special interface for each of their customers which would result in huge complexity problems they are following the approach to apply a rather flexible interface suitable for different kind of customers.		
Strong Dependencies		
Company Importance	Smaller companies often are not able to dictate their very own product specifications to their customers especially in case they have a rather big customer which is often the case if companies are suppliers to big organization such as automotive manufacturers (4), Smaller relatively unimportant companies are further often only one part of a system. In order to ensure high compatibility of the connected ecosystem they have to be flexible (3)	Low Importance – High Flexibility
Customer Variety	Especially in case of high customer variety a rather flexible signal layer should be applied in order to adapt to very different customer systems to be connected to (2)	High Variety – High Flexibility
Weak Dependencies	- System Openness - Standardization - Compatibility	**Strong Effects**
References: (1) Interview 4, (2) Interview 6, (3) Porter & Heppelmann, 2014, (4) Interview 10		P10

II	**Security** **(Signal Layer)**	low high
Security of the Signal Layer concerns the cybersecurity properties of a system capable to prevent malicious attacks to the system or to the data shared within the system. According to (1) security concerns are the biggest barrier to success in the area of IoT. Various interviewees stated that these concerns significantly affect the way connectivity is utilized. Since they have not found appropriate security solutions protecting their signal layer many companies utilize only one-directional connectivity functions (2, 3)		(1) (2)
Strong Dependencies		
Regulation	High regulations showed to come along in many cases with rather high concerns in terms of secure interfaces in order to ensure safety of the operators	High regulation – High Security
Cybersecurity Requirements	Cybersecurity requirements result in most aspects into highly secure architectures	High Cybersecurity – High Security
Privacy Requirements	Data privacy requirements result in most aspects into highly secure architectures	High Privacy Requirements – High Security
Data Direction	In order to create rather secure architectures in terms of functional safety many companies do so far only apply a one-directional data transferring approach in their product concepts in order to prevent malicious attackers from accessing control functions of the product. (2) and (3) stated that there are indeed potential applications for a two-directional data-transfer, however the value is not big enough to take the risk for them	One-diectional data exchange – High Security
Weak Dependencies	- System Openness - Compatibility	**Strong Effects**: - Data Direction - Lifetime Responsibility
References: (1) Ganguli & Friedman, 2017, (2) Interview 1, (3) Interview 9, (4) Interview 4		P11

II	**Compatibility** **(Signal Layer)**	low high
The compatibility of an architecture defines which components of the connected eco-system can connect to the product. According to (1) the degree of compatibility is one important factor concerning the system's complexity. Thus, when defining how much compatibility should be provided by the product it must be thought on the other hand how much complexity can be managed. Due to the rapid technological change of several different components of the system complexity can grow rapidly if for example compatibility to all previous software versions should be ensured		(2) (1)
Strong Dependencies		
System Openness	Compatibility is one of the most important characteristics for an open system approach, since it defines to some degree how open the system actually is.	Open System – High Compatibility
		-
		-
		-
Weak Dependencies	- Service Strategy - Cybersecurity Requirements - Privacy Requirements - Standardization - Flexibilty	**Strong Effects**: - Virtual Testing - Ecosystem Thinking - Complexity Management
References: (1) Interview 6 (2) Interview 1		P12

II	**Data Direction** (Connectivity Layer)	One-Directional — Two-Directional
The Data Direction refers to the fact in which direction data is exchanged in the system and has thereby a major impact on the connected functions which can be provided by the product. Considering the IoT maturity scheme outlined by (1) one-directional data exchange results only in rather basic IoT applications such as monitor/send-only or control-only In many cases monitor/send-only functions are the first applications initiated when companies moving towards more connected products. Often this is especially due to cybersecurity concerns (2, 3). However, besides that data direction is in some cases basically dependend on the use-case		(2, 3)
Strong Dependencies		
Regulation	(2) and (3) both apply only functions based on one-directional data transfer. They stated that there are indeed potential applications, however they have not developed appropriate security solutions, which results in the fact that they limited the data-transfer direction to one-directional transfer in order to avoid malicious attackers accessing control functions	High Regulation – One-Directional Data Transfer
Cybersecurity Requirements	(2) and (3) both apply only functions based on one-directional data transfer. They stated that there are indeed potential applications, however they have not developed appropriate security solutions, which results in the fact that they limited the data-transfer direction to one-directional transfer in order to avoid malicious attackers accessing control functions	High Cybersecurity Requirements – One-Directional Data Transfer
-	-	-
-	-	-

Weak Dependencies	- Service Strategy - Implementation Pace Strategy - Architectural Focus - Modularity In-Use/In-Design - Frequency of Connection	**Strong Effects**	- Security

References: (1) Porter & Heppelmann, 2014, (2) Interview 1, (3) Interview 9, (4) Interview 6 P13

II	**Frequency of Connection** (Connectivity Layer)	low — high
Frequency of connection refers to the fact whether data is transferred continuously or only to a specific point in time. Besides of the dependencies listed below this of course depends on the use case as well. (1) further stated that in their example they do sometimes not even have the choice since their products in same cases operates in regions where no mobile network is available, which in such occasions requires to store data to be transferred in the meanwhile. (2) and (4) for example represent use cases which do not require contionous data transfer and thus a high frequency of connection		(1) (2)
Strong Dependencies		
Service Strategy	The frequency of connection and data transfer has to align with the service strategy and the actual nature of the service. Since it can be said that when the frequency of connection is low, so is the frequency of servicing. For (1) the service does for example does not fully depend on continuous data transfer. Moreover, the service is rather a nice-to-have and the product's main function is independent on data transfer.	Product focus – Low Frequency of connection
Architectural Focus	Depending on the architectural focus of the product the frequency of connection might not be optional. Considering products where crucial functions are located in the cloud such as Amazon Echo (2) continuous data transfer is required, since otherwise the product does not work. If the majority of functions are implemented in the actual product lower data transfer frequencies are possible	Cloud Focus – High Frequency of Connection

Weak Dependencies	- Connection Type	**Strong Effects**	- Data Storage Capabilities

References: (1) Interview 9, (2) Amazon.com, 2019, (3) Interview 4 P14

II	Connection Type (Connectivity Layer)	Local Network — Mobile Network
The connection type describes if a local network or a mobile network is utilized for the data transfer. This is to some extent depended on certain strategy and market aspects ,however ultimately determined by the use case. Production machinery such as (1) and (2) are for example usually connected by a local network which enables transmitting large amount of data continuously. The product of (3) on the other hand is used at different locations and thus is in most situations connected to the cloud via mobile network. Further, utilizing a mobile network requires the collaboration with network providers in order to deliver the full service (3, 5)		(1,2) (3)
Strong Dependencies		
Architectural Focus	Similarly to the Frequency of Connection the architectural focus might require continuous servicing such as in the case of Amazon Echo (4) which is fully cloud focused. Utilizing a mobile network for a product which is mainly cloud focus bears the risk of service interruption and thereby also interruption of the product's function	Cloud Focus – Local Network Connection
		-
		-
		-

Weak Dependencies	- Frequency of Connection	**Strong Effects**	- Data Storage Capabilities

References: (1) Interview 6, (2) Interview 8, (3) Interview 9, (4) Amazon.com, 2019, (5) Interview 5 P15

II	Data Storage Capabilities (Connectivity Layer)	low — high
The necessity for data storage is especially given in the cases where data transfer cannot be assured the whole time. In this case it is necessary to store the data until the next possibility to transfer the data. This is in most cases depended on the use case.		(2) (1)
Strong Dependencies		
Frequency of Connection	In the case frequency of connection is low, data cannot be continuously transmitted and thus data storage capabilities must be present. This can for example occur if a product is used in remote areas such as the case for (1), which is utilized to build infrastructure or (3) which is utilized in agriculture areas.	Low Frequency of Connection – High Data Storage Capabilities
Connection Type	If a mobile network is utilized reliable data transfer cannot be assured to any point in time. In case frequency of connection is low, data cannot be continuously transmitted and thus data storage capabilities must be present. This can for example occur if a product is used in remote areas such as the case for (1), which is utilized to build infrastructure or (3) which is utilized in agriculture areas.	Mobile Network Connection – High Data Storage Capabilities

Weak Dependencies	- Architectural Focus	**Strong Effects**	- External Collaborations

References: (1) Interview 9 (2) Amazon.com , 2019, (3) Interview 5 P16

III	**Agility** (Organization)	Waterfall Agile
Organizational Agility refers in contrast to agile development processes to the fact whether agile teams are empowered to perform their work in a fully agile manner without getting slowed down by organizational structures, which might not allow the empowerment of agile development team. The need for organizational agility was specifically mentioned by (1). It was concluded that this is especially due to the fact that the actual architecture applied in the case of (1) is rather agile, too, due to the agile upgradeability type and high In-use scalability. (2) in contrast did not see the need for changing their organization, however the applied architecture is not agile, either.		(2) (1)
Strong Dependencies		
Upgradeability Type	The Upgradeability type defines whether the updates to be implemented during the usage phase are pre-defined during roll out of the product or if a rather agile approach is applied. A predefined upgradeability approach does not necessary require an organizational change towards more agility because the product is actually delivered in a waterfall manner such as the case for (2)	Agile Upgradeability Type – Agile Organization
In-Use Scalability	In case only a basic version of the product is delivered during the roll out in order to cut development lead times and then continuously scaling up the functionalities such as applied by (1) it is really important to empower the agile development teams to implement the functions necessary continuously into the product. Otherwise the planned capabilities will be unused for too long	High In-Use Scalaibility – Agile Organization
Weak Dependencies	- Modularity In-Use - Modularity In-Design - Additional Capacities	**Strong Effects**
References: (1) Interview 4, (2) Interview 9,		O1

III	**Modularity** (Organization)	Integral Modular
According to (1) the principles of modularity from the product architecture perspective can be applied to organizational architectures, too. They define a modular organization as organizational units, which have a clearly defined area of responsibility, where they are able to make decision in. They further state that the degree of modularity in terms of the product architecture has to align with the modularity of the development architecture in order to fully benefit from the modularity in both fields.		(1) (2)
Strong Dependencies		
Modularity In-Use	According to the connection between organizational modularity and product architecture modularity as outlined by (1) both these aspects have align with each other in order to ensure effective development.	High Modularity In-Design – High Organizational Modularity
Modularity In-Design	According to the connection between organizational modularity and product architecture modularity as outlined by (1) both these aspects have align with each other in order to ensure effective development.	High Modularity In-Use – High Organizational Modularity
		-
		-
Weak Dependencies	- Upgradeability Type - In-Use Scalability - System Openness - Standardization - Definition Clearity	**Strong Effects**
References: (1) Göpfert & Steinbrecher, 2000		O2

III	**Risk Taking Ability** (Organization)	low high
The ability of an organization to take risks was specifically outlined by (1) with regards to the large technology driven change associated with the emergence of more connected functionalities. Due to the rapid technological changes companies, who are depended on usage of industry standards are forced to take some degree of risk when implementing new technologies, since it might be the case that the chosen immature technology is not technologically sustainable and they are forced to change certain components in order to keep up with technological standards		(1)
Strong Dependencies		
Modularity in Design	According to (1) it is key to apply a modular architecture in order to be able to take the risk when implementing newly emerging technologies. (1) stated that they had problems with changing technologies because the architecture they have build was not capable to easily implement a new component without changing other parts of the architecture, too. Following a modular architecture would reduce the impact of changing technologies	In-Use modular Architecture – High Risk Taking Ability

Weak Dependencies	- System Opennenss - Architectural Focus - Modularity In-Use - Additional Capacities - Standardization	**Strong Effects**	
References: (1) Interview 10			O3

III	**Virtual Testing** (Processes)	low high
The need to enable virtual testing was mentioned by (1) and (2) and refers to the process of applying tools in the development process that enable virtual testing of the system especially in collaboration with external developers. This is of further importance due to the fact that these changes of the system not only occur in connected products during the design phase but also during the actual usage phase. In order to prevent the user from experiencing interruptions testing should be performed virtually on virtual mock-ups and not on the running system.		(1) (2)
Strong Dependencies		
Upgradeability Type	The way upgrades are enabled and implemented to a connected system determines if there is a need for virtual testing. The impact of pre-defined updates is usually already validated and thus does not require further means of testing before they get activated or deactivated. However, especially in collaborations with external developers, it is important to provide them with the ability for virtual testing before implementation (1)	Agile Upgradeability – High Need for Virtual Testing
Compatibility	(2) mentioned the need for virtual testing especially with regards to the complexity associated with high compatibility, because these complexity issues are fairly hard to manage in highly connected system.	High Compatibility – High Need for Virtual Testing

Weak Dependencies	- In-Use Scalability - Standardization - Definition Clearity - Flexibility	**Strong Effects**	-
References: (1) Interview 4 (2) Interview 6			PR1

III	External Collaboration (Processes)	low — high
The need or ability for external collaboration is indeed highly depended on strategical aspects such as the make-or-buy strategy, company importance or development depth. However, they are not considered in the conducted dependency analysis. But there are yet architectural aspects impacting conditions for external collaboration.		
Strong Dependencies		
Modularity In-Design	According to (1) and (2) Modularity In-Design can directly be related with R&D issues such as product development management. Here especially the need for clearly defined interfaces must be mentioned enabling so-called black box development and facilitating communication	Modular Architecture – High Ability for External Collaboration
Connection Type	Besides external collaborations aiming towards specific development activities (3) and (4) mentioned the need for external development with network providers in case they are utilizing a mobile network. This is important in order to evaluate if utilizing the network provider's services for data transfer is economically feasible. (3) stated that such a collaboration was not established before and can be challenging especially for smaller companies	Mobile Network Connection – Need for External Collaboration
-	-	-
-	-	-

Weak Dependencies	- System Openness - Architectural Focus	**Strong Effects**	

References: (1) Ulrich & Eppinger (2) Baldwin and Clark, 2000, (3) Interview 5, (4) Interview 9 PR2

III	Ecosystem Thinking (Processes)	low — high (1)
Ecosystem Thinking can be according to (1) be referred to as rethinking the way value is created in a connected system. By considering the system as a connected ecosystem rather than as the sum of stand-alone products new value can be created. However, consequently this value is then also depended on the connectivity.		
Strong Dependencies		
System Openness	In general, companies should be aware that the system openness impacts the ecosystem properties significantly. A rather open system is especially useful because it enables external developers easily to contribute in building the connected ecosystem. A closed ecosystem on the other hand results in the fact that the company itself has to build this ecosystem or is responsible for assigning tasks to selected external developers such as in the case of (1)	Open System – High Ecosystem Thinking
Compatibility	Compatibility is an important aspect when building a connected ecosystem since it defines which components can provide value for the ecosystem. Thereby it should however be considered that compatibility is somehow always connected with complexity (2). Thus, companies should consider this trade-off when they apply ecosystem thinking	High Compatibility – High Ecosystem Thinking
Standardization	A way to collaboratively create a connected ecosystem beyond the own product portfolio is to utilize standards in the signal layer. This facilitates working with external partners and further might create an even bigger ecosystem by giving the possibility to connect to products out of a company's own reach. (1) for example stated that industry-specific standards could make sense, however are difficult to establish due to competitiveness	Industry Standards – High Ecosystem Thinking
		-

Weak Dependencies	- Architectural Focus	**Strong Effects**	

References: (1) Interview 4 (2) Interview 6 PR3

III	Lifetime Responsibility (Processes)	low high
(1) and (2) both stated that one biggest challenges of the implementation of connected functions is that the responsibility for the product does not end after selling it to the customer. Now historically product focused companies more and more have to implement services ensuring the product's functionalities over the entire life time. One reason for this is certainly that the element the product is connected to changes over the lifetime , which in many cases requires the product to adapt to these changes, too. This responsibility can, however also be seen as an opportunity for companies to deliver continuous value to their customers		
Strong Dependencies		
In-Use Scalability	In case high In-Use Scalability is utilized lifetime responsibility is turned further into a opportunity, which is for example used by (4) and (6), which both have released a product providing only basic functionalities but however already featured the necessary hardware enabling more sophisticated functions. The responsibility in this case lies in the fact that the customers expects to achieve more functions over the lifetime of the product.	High In-Use Scalability – High Lifetime Responsibility
Security	Especially in terms of security lifetime responsibility plays a crucial role since only by providing continuous updates over the entire lifetime of the product the security standards can be kept up to date (5)	High Security – High Life Time Responsibility
Weak Dependencies	- System Openness - Architectural Focus - Modularity In-Use - Upgradeability Type - Compatibility	**Strong Effects**
References: (1) Interview 5, (2) Interview 9, (3) Interview 4, (4) Interview 6, (5) Hsu, 2017		PR4

III	Long-term Thinking (Processes)	low high
Especially due to the fact the technology with regards to IoT is continuously changing, companies have to think ahead if they depend on such market standards and are not capable to dictate their technical specifications. Such a long-term thinking must be used to predict what technologies will be stable over the life of the product on the one hand but also to consider how easy transition is achieved once new technologies are implemented.		
Strong Dependencies		
Modularity In-Design	Modularity in design is clearly a way how companies express their long-term thinking in a practical way. A modular architecture does not provide value for a company in the short term but (1) predicts for example that they have to change certain component frequently because it is not available any more between two successive product generations	Modular Architecture – High Longterm Thinking
Modularity In-Use	Modularity In-Use is similarly to Modularity In-Design a means for companies to think in the long-term and keeping their current product long on the market by ensuring new technology can be implemented throughout the life time. (2) for example stated that they do not consider exchanging hardware throughout the life cycle because they do not plan in the long-term	Modular Architecture – High Long-term Thinking
Additional Capacity	An alternative for modularity In-Use is the implementation of additional capacities into products, which enables to integrate new technology without the need for exchanging elements. However, this requires companies to be aware of what functions they are going to implement in the future	Many Additional Capabilities – High Long-term Thinking
Weak Dependencies	- System Openness - Architectural Focus	**Strong Effects** -
References: (1) Interview 10, (2) Interview 1, (3) Interview 4		PR5

III	Complexity Management (Processes)	low high
According to (1) and (2) especially the design of the signal layer is associated with a high degree of complexity. In order to deal with this issue companies should apply some form of complexity management. However, the degree of complexity and thereby the need for an effective complexity management depends to some extent on the architectural design of the connected E/E system		
Strong Dependencies		
System Opennness	The openness of the system affects the complexity significantly since it defines how many elements are connected to the product. Further, it is associated with the fact how much influence the company has on the fact, which elements are connecting to it. An open system will be most likely connect to significantly more elements than a closed one	System Openness – High need for Complexity Management
Compatibility	The level of compatibility of the system has as significant impact on its complexity. According to (6) it is important to consider how much compatibility is aimed. For example by enabling compatibility between two different software versions (2 X 2) the complexity can be significantly be reduced in comparison to enabling compatibility between three different versions (3 X 3)	High Compatibility – High need for Complexity Management
Upgradeability Type	Different Upgradeability approaches result into different complexity levels to be managed during the usage phase. (3) for example only implements pre-defined updates throughout the usage, which reduces the complexity significantly	Pre-defined Upgradeability – Low need for Complexity Management

Weak Dependencies	- Standardization - Definition Clearity	**Strong Effects**	

References: (1) Interview 4, (2) Interview 6, (3) Interview 9 PR6