SUPPORTING DEVELOPERS IN ADDRESSING MAINTENANCE ASPECTS

an empirical study in the industrial equipment manufacturing industry

WIENIK MULDER

SUPPORTING DEVELOPERS IN ADDRESSING MAINTENANCE ASPECTS

AN EMPIRICAL STUDY IN THE INDUSTRIAL EQUIPMENT
MANUFACTURING INDUSTRY

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
Prof.dr. H. Brinksma,
on account of the decision of the graduation committee,
to be publicly defended
on Wednesday the 1st of June 2016 at 12:45

by

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PhD Thesis, University of Twente, Enschede, the Netherlands

ISBN: 978-90-365-4059-9

DOI: 10.3990/1.9789036540599

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This research has been funded by Lloyd's Register Foundation. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research.

Summary

Addressing maintenance aspects has become increasingly important in development projects of industrial equipment. Developers of such equipment need to address the maintenance aspects in order to achieve competitive equipment and service offerings. To do so, the literature proposes to apply approaches in which the equipment and service elements, among which maintenance, are addressed in an integrated way. This research contributes to the knowledge on how such integrated offerings can be successfully developed. It focuses on the identification of the maintenance aspects that are relevant to be addressed in development project and on how developers can successfully do this. The ultimate goal of the research is to support developers in addressing maintenance aspects in development projects in practice.

The research consists of a descriptive and a prescriptive study. The descriptive study focuses on eliciting knowledge from experts in companies and proposing overviews that represent this knowledge in a usable way. Experts from three Dutch industrial equipment providers are involved. I have used in-depth interviews and validation sessions to gather their knowledge. Based on the information that was retrieved from the in-depth interviews, I have developed (1) a model of relevant maintenance aspects to be addressed in development projects, (2) an overview of development activities that developers perform to address these aspects and (3) an overview of factors that affect whether the maintenance aspects are addressed successfully. During the validation sessions, I have presented the model and overviews to experts at the same companies and I have asked for their feedback. Based on the retrieved feedback, I have made a number of improvements. The prescriptive study focuses on describing design support that is useful to support developers in addressing the maintenance aspects. From the results of the descriptive study, I have reasoned that different types of support can be useful. I propose three types of concrete supporting tools and describe how these could help developers in addressing the maintenance aspects.

The model of relevant maintenance aspects gives an overview of the maintenance aspects that are relevant to address and organizes them in three categories, according to the way in which developers use them to make design decisions. The three categories are *performance aspects*, *scenario aspects* and *equipment design / maintenance service design aspects*. Performance aspects represent the maintenance related performance indicators that developers can define and use to evaluate the outcome of development activities. Examples are the frequency of maintenance actions and the time required for a maintenance task. Scenario aspects are the external factors that affect the performance levels that can be achieved, such as the environmental conditions in which the equipment is to be operated and the knowledge and skill levels of service engineers. They are outside the direct range of influence of developers, but developers need to anticipate them when making design decisions. Equipment design / maintenance service design aspects represent the characteristics and properties of the equipment, the maintenance deliverables and elements of the maintenance delivery services. Examples are the equipment modularity, maintenance diagnostics tools and maintenance support services. To properly address the maintenance aspects, the research shows that developers should consider the interrelations between the equipment design, the maintenance service design and the elements of the environment in which the equipment is operated and maintained. Also, it is important to consider that not all aspects should or can always be addressed. The relevance of addressing particular aspects is related to the goal of the development project and the stage in which a development project is.

The overview of development activities describes ten activities that developers perform to address the maintenance aspects. The activities take place throughout all stages of development project. They are: (1) defining and specifying requirements, (2) everyday discussions, (3) design reviews, (4) analyses of wear and failure behavior, (5) analyses of maintenance performance, (6) testing activities, (7) maintenance service design activities, (8) making improvements during the pilot run, (9) developing upgrades and improvements during the use and support life cycle phases and (10) gathering and analysis of data and feedback. The research shows that it is most important and challenging to address the maintenance aspects successfully during the early stages of a development project. It is especially challenging to explicitly analyze and evaluate the effect of equipment design decisions on the performance of maintenance.

The overview of factors describes fourteen factors that affect whether the maintenance aspects are addressed successfully: (1) knowledge on maintenance aspects, (2) availability and quality of data, (3) availability and quality of feedback, (4) knowledge on the existing installed base, (5) quality of definition and use of performance indicators and requirements, (6) availability and usability of methods/tools to support addressing maintenance aspects, (7) timing of addressing maintenance aspects, (8) launch timing, (9) the extent to which addressing maintenance aspects is embedded in the development process, (10) supplier involvement, (11) customer involvement, (12) quality of communication, (13) individual quality and skills of developers and (14) company organizational and cultural aspects. Taking an overarching look at these factors provides three core insights. Firstly, the importance that is given to maintenance aspects strongly affects whether or not maintenance aspects are explicitly addressed. Secondly, the knowledge of project teams and the knowledge and skills of individual developers are of key importance to ensure that maintenance aspects are addressed and that good design decisions are made. Thirdly, there is a strong dependence on data and feedback from the field to conduct meaningful analyses.

As a result of the prescriptive study, I propose three tools that are meant to provide overview to developers and help them to address the maintenance aspects systematically. The three tools provide support on three different levels of product development, namely the strategic, tactical and operational level. For the strategic level, the use of the model and the two overviews that are developed as part of the descriptive study is proposed. This support aims to stimulate developers to explicitly discuss the maintenance aspects when a new equipment development project is started. For the tactical level, a maintenance performance calculation matrix is suggested. It supports the quantitative analysis of the maintenance performance and helps developers to systematically discuss and identify the most important aspects to focus on in a development project. Finally, for the operational level, a set of design-for-maintenance guidelines is recommended. Similar to the first tool, it supports in discussing the maintenance aspects explicitly. Since only an initial prescriptive study is performed, the use and effect of the proposed tools need further investigation.

The overall conclusion is that, in industrial equipment manufacturing companies, vast knowledge exists about the maintenance aspects that are relevant to address and about how they can be addressed successfully. The main contribution of this research is that it has made this knowledge of developers explicit and has synthesized it in a holistic way. The developed model and the developed overviews provide a complete overview of the relevant maintenance aspects and the way to address them. This provides a starting point for companies that want to address maintenance aspects better. Furthermore, the research gives a starting point for further development of design support that fits the needs of developers in practice.

For continuation of the research, I firstly propose to investigate the extent to which the research results can be generalized and applied to other types of technical systems and their development

processes. Secondly, it would be interesting to investigate the similarities and differences between companies and industries with respect to the aspects that are relevant to address. Finally, it would be useful to investigate how to support the provision of good feedback during a development project. Besides the continuation of the research, I see the relevance of taking other perspectives when further developing the understanding of addressing maintenance aspects. For example, the research topic could be investigated from the perspective of the users of industrial equipment. Finally, I also think it is valuable to integrate knowledge from other research areas. For example, integration of knowledge from the area of production development (in contrast to product development) is likely valuable when it concerns the development of integrated solutions of equipment and services.

Samenvatting

Onderhoudsaspecten worden steeds belangrijker in ontwikkelprojecten van industriële systemen. Voor ontwikkelaars van dergelijke systemen is het belangrijk om aandacht te geven aan onderhoudsaspecten. Dat is nodig om competitieve systemen en services te realiseren. De literatuur stelt voor om hiervoor een aanpak te kiezen waarin het ontwerpen van de fysieke machines en het ontwerpen van de bijbehorende services, waaronder onderhoud, worden geïntegreerd. Dit onderzoek draagt bij aan de kennis over hoe zulke geïntegreerde oplossingen succesvol kunnen worden ontwikkeld. Het onderzoek richt zich op de identificatie van de onderhoudsaspecten die relevant zijn om mee te nemen in een ontwikkelproject en op hoe dat succesvol gedaan kan worden. Het doel van het onderzoek is het ondersteunen van ontwikkelaars in het meenemen van de onderhoudsaspecten tijdens ontwikkelprojecten in de praktijk.

Het onderzoek bestaat uit een descriptieve en een prescriptieve studie. De descriptieve studie focust op het achterhalen van de kennis van deskundigen in bedrijven en de ontwikkeling van overzichten om deze kennis op een bruikbare wijze weer te geven. Deskundigen van drie Nederlandse leveranciers van industriële systemen zijn hierin betrokken. Ik heb gebruikt gemaakt van diepte-interviews en validatiesessies om hun kennis te vergaren. Op basis van de informatie die is vergaard tijdens de diepte-interviews, heb ik het volgende ontwikkeld: (1) een model van de relevante onderhoudsaspecten die meegenomen kunnen worden in een ontwikkelproject, (2) een overzicht van ontwikkelactiviteiten die ontwikkelaars uitvoeren om deze aspecten mee te nemen en (3) een overzicht van factoren die invloed hebben op het succes waarmee de onderhoudsaspecten worden meegenomen. Tijdens de validatiesessies heb ik het model en de overzichten voorgelegd aan de deskundigen bij dezelfde bedrijven en heb ik naar hun feedback gevraagd. Gebaseerd op deze feedback heb ik een aantal verbeteringen aangebracht. De prescriptieve studie focust op het beschrijven van ontwerpondersteuning die nuttig kan zijn voor ontwikkelaars. Vanuit de resultaten van de descriptieve studie heb ik beredeneerd dat verschillende typen ontwerpondersteuning nuttig kunnen zijn. Ik stel drie verschillende typen ondersteunende gereedschappen voor en beschrijf hoe deze ontwikkelaars kunnen helpen in het meenemen van de onderhoudsaspecten tijdens een ontwikkelproject.

Het model van de relevante onderhoudsaspecten geeft een overzicht van de onderhoudsaspecten die ontwikkelaars aandacht kunnen geven en organiseert deze in drie categorieën. Deze categorieën volgen de wijze waarop ontwikkelaars de aspecten gebruiken om ontwerpbeslissingen te maken. De drie categorieën zijn *performance aspects* (prestatie-aspecten), *scenario aspects* (scenario-aspecten) en *equipment design / maintenance service design aspects* (machine- en/of onderhoudsservice-ontwerpaspecten). *Performance aspects* representeren de prestatie-indicatoren die ontwikkelaars kunnen definiëren en kunnen gebruiken voor het evalueren van de uitkomsten van ontwikkelactiviteiten. Voorbeelden zijn de frequentie van onderhoudstaken en tijd die nodig is voor het uitvoeren van een onderhoudstaak. *Scenario aspects* zijn de externe factoren die invloed hebben op de prestatieniveaus die gerealiseerd kunnen worden, zoals de omgevingscondities waarin de machines worden gebruikt en de kennis en vaardigheden van onderhoudsmonteurs. Ontwikkelaars kunnen deze aspecten niet direct beïnvloeden, maar zij kunnen hierop anticiperen bij het maken van ontwerpbeslissingen. *Equipment design / maintenance service design aspects* zijn de kenmerken en eigenschappen van de machines, onderhoud gerelateerde documenten, en elementen van de te leveren onderhoudsservices. Voorbeelden zijn de modulariteit van de machines, onderhoudsdiagnosegereedschappen en onderhoud ondersteunende diensten. Het onderzoek laat zien dat het succesvol meenemen van onderhoudsaspecten inhoudt dat

ontwikkelaars moeten kijken naar de onderlinge relaties tussen het machine-ontwerp, het onderhoudsservice-ontwerp en de elementen van de omgeving waarin de installaties gebruikt en onderhouden gaan worden. Bovendien is het belangrijk om te realiseren dat niet alle aspecten altijd moeten of kunnen worden meegenomen. De relevantie voor het meenemen van bepaalde aspecten is gerelateerd aan het doel van een ontwikkelproject en de fase waarin een ontwikkelproject zich bevindt.

Het overzicht van ontwikkelactiviteiten beschrijft tien activiteiten die ontwikkelaars uitvoeren en waarin onderhoudsaspecten mee worden genomen. De tien activiteiten vinden plaats in alle fasen van een ontwikkelproject. Het zijn: (1) definiëren en specificeren van eisen, (2) dagelijkse discussies, (3) ontwerpreviews, (4) analyses van slijtage en faalgedrag, (5) analyses van de onderhoudsprestaties, (6) testactiviteiten, (7) onderhoudsservice-ontwerpacтивiteiten, (8) het maken van verbeteringen gedurende een proefproject, (9) ontwikkelen van upgrades en verbeteringen tijdens de gebruiks- en ondersteuningslevenscyclusfasen en (10) verzamelen en analyseren van data en terugkoppeling. Het onderzoek laat zien dat het erg belangrijk is, en ook het meest uitdagend, om de onderhoudsaspecten succesvol mee te nemen tijdens de vroege fasen in een ontwikkelproject. Expliciet analyseren en evalueren wat het effect is van beslissingen omtrent het machine-ontwerp op de uiteindelijke onderhoudsprestaties is in het bijzonder een uitdaging.

Het overzicht van factoren beschrijft veertien factoren die invloed hebben op het succes waarmee onderhoudsaspecten worden meegenomen. De factoren zijn: (1) kennis over onderhoudsaspecten, (2) beschikbaarheid en kwaliteit van data, (3) beschikbaarheid en kwaliteit van terugkoppeling, (4) kennis over de bestaande geïnstalleerde systemen, (5) kwaliteit van de definitie en het gebruik van prestatie-indicatoren en eisen, (6) beschikbaarheid en bruikbaarheid van methoden/gereedschappen ter ondersteuning van het aanpakken van onderhoudsaspecten, (7) timing van het meenemen van onderhoudsaspecten, (8) timing van het op de markt brengen van het systeem, (9) de mate waarin het meenemen van onderhoudsaspecten is ingebed in het ontwikkelproces, (10) betrokkenheid van leveranciers, (11) betrokkenheid van klanten, (12) kwaliteit van communicatie, (13) individuele kwaliteit en vaardigheden van ontwikkelaars en (14) bedrijfsorganisatorische en culturele aspecten. Wanneer over deze factoren heen wordt gekeken, worden drie belangrijke inzichten verkregen. Ten eerste is het belang dat wordt gehecht aan de onderhoudsaspecten sterk van invloed op het al dan niet expliciet meenemen ervan gedurende een ontwikkelproject. Ten tweede zijn de kennis in een projectteam en de kennis en vaardigheden van individuele ontwikkelaars van het groot belang om ervoor te zorgen dat onderhoudsaspecten worden meegenomen en dat goede ontwerpkeuzes worden gemaakt. Ten derde is er een sterke afhankelijkheid van gegevens en terugkoppeling uit het veld om zinvolle analyses te kunnen maken.

Als resultaat van de prescriptieve studie stel ik drie ondersteunende gereedschappen voor die bedoeld zijn om overzicht te geven aan ontwikkelaars en hen te helpen om de onderhoudsaspecten systematisch mee te nemen. De drie gereedschappen bieden ondersteuning op drie verschillende niveaus van productontwikkeling, namelijk het strategische, tactische en operationele niveau. Voor het strategische niveau stel ik voor: het gebruik van het model en de twee overzichten die ontwikkeld zijn als onderdeel van de descriptieve studie. Dit gereedschap heeft als doel om ontwikkelaars te stimuleren dat onderhoudsaspecten expliciet worden bediscussieerd wanneer een nieuw ontwikkelproject wordt gestart. Voor het tactische niveau wordt een berekeningsmatrix voorgesteld. Deze ondersteunt het maken van kwantitatieve analyses van de onderhoudsprestaties en ondersteunt in het systematisch bediscussiëren en identificeren van de belangrijkste aspecten in een ontwikkelproject. Ten slotte, voor het

operationele niveau wordt een set van ontwerprichtlijnen aanbevolen. Net zoals het eerst voorgestelde gereedschap ondersteunt deze ook het expliciet meenemen van de onderhoudsaspecten. Omdat er een initiële prescriptieve studie is uitgevoerd, moet het gebruik en het effect van de voorgestelde gereedschappen nog verder worden onderzocht.

De algemene conclusie van het onderzoek is dat er veel kennis aanwezig is in bedrijven die industriële systemen ontwikkelen over onderhoudsaspecten en over hoe deze succesvol kunnen worden meegenomen. De belangrijkste bijdrage van dit onderzoek is dat het deze kennis van ontwikkelaars expliciet heeft gemaakt en het heeft samengevoegd op een holistische wijze. Het ontwikkelde model en de ontwikkelde overzichten bieden een compleet beeld van de relevante onderhoudsaspecten en de wijze waarop deze succesvol kunnen worden meegenomen. Dit biedt een startpunt voor bedrijven die onderhoudsaspecten beter willen aanpakken. Verder geeft het onderzoek een startpunt voor verdere ontwikkeling van ontwerpondersteuning die aansluit bij de behoeften van ontwikkelaars in de praktijk.

Voor voortzetting van het onderzoek stel ik voor om, ten eerste, te onderzoeken in hoeverre de onderzoekresultaten kunnen worden gegeneraliseerd en toegepast kunnen worden op andere type technische systemen en de gerelateerde ontwikkelprocessen. Ten tweede zou het interessant zijn om de overeenkomsten en verschillen tussen bedrijven en sectoren te onderzoeken wat betreft de aspecten die relevant zijn om mee te nemen. Ten slotte zou het nuttig zijn om te onderzoeken hoe het verstrekken van goede terugkoppeling ondersteund kan worden tijdens een ontwikkelproject. Naast de voortzetting van het onderzoek zie ik het belang van het nemen van andere perspectieven om verdere kennis te ontwikkelen over hoe onderhoudsaspecten meegenomen kunnen worden. Zo zou bijvoorbeeld het onderzoeksonderwerp kunnen worden onderzocht vanuit het perspectief van de gebruikers van industriële systemen. Tot slot denk ik ook dat het waardevol is om kennis te integreren uit andere onderzoeksgebieden. Kennis vanuit het gebied van productieontwikkeling (in tegenstelling tot productontwikkeling) zou bijvoorbeeld waardevol kunnen zijn wanneer het gaat om de ontwikkeling van geïntegreerde oplossingen van producten en services.

Table of contents

1	Introduction	1
1.1	Industrial equipment and maintenance	1
1.2	Changing business activities of equipment manufacturers	3
1.3	Product development	5
1.4	Research motivation	7
1.5	Research goal	9
1.6	Research approach and research questions	9
1.7	Contribution	11
1.8	Outline of the thesis	12
2	State of the art literature on addressing maintenance aspects	15
2.1	State of the art on relevant maintenance aspects	16
2.2	State of the art on how to address maintenance aspects	22
2.3	Conclusion	27
3	Introduction to the empirical study and relevance of addressing maintenance aspects	29
3.1	Introduction to the empirical study	29
3.2	Relevance of addressing maintenance aspects	35
3.3	Conclusion	40
4	Relevant maintenance aspects to be addressed	41
4.1	Model of relevant maintenance aspects	41
4.2	Illustration of the relevance of the individual aspects	49
4.3	Relevance of maintenance aspects during a development project	55
4.4	Conclusion	59
5	How maintenance aspects can be addressed	61
5.1	The role of maintenance aspects in different development process stages	61
5.2	Development activities that developers perform to address maintenance aspects	64
5.3	Factors that affect whether maintenance aspects are addressed successfully	72

5.4 Lessons learned regarding how maintenance aspects can be addressed successfully	81
5.5 Conclusion	83
6 Support for addressing maintenance aspects	85
6.1 Insights obtained from the Descriptive Study	85
6.2 Support 1 – Overview of relevant maintenance aspects, activities and factors	88
6.3 Support 2 – Maintenance performance calculation matrix	89
6.4 Support 3 – Set of design-for-maintenance guidelines	92
6.5 Conclusion	94
7 Conclusion	97
7.1 Conclusion	97
7.2 Discussion	100
7.3 Further research	102
Bibliography	105
Appendices	111
Appendix I - RMS in the systems engineering process	113
Appendix 2 - Interview guide used in the empirical study	115
Appendix 3 - Examples of parts of the in-depth interviews	124
Appendix 4 - Illustrations of the prepared mind maps	125
Appendix 5 - Information retrieval questions used in the empirical study	128
Appendix 6 - Initial findings	129
Appendix 7 - Feedback form used in the empirical study	139
Appendix 8 - Answers to questions at the feedback forms	142
Appendix 9 - Additions to initial findings	145
Appendix 10 - Comparison overviews of development activities	146
Appendix 11 - A set of design-for-maintenance guidelines	149
Acknowledgements	153

I Introduction

Development of industrial equipment is a challenging activity. Nowadays, such equipment, like food processing lines, manufacturing machines and material handling systems is highly complex and advanced. It contains many mechanical, electronic and software sub-systems and components that interact with each other, with the environment and with the user. The design of these sub-systems and components, their integration in the final product and many other aspects must be addressed during the development of the equipment. Maintenance aspects also must be addressed. They have become increasingly important for industrial equipment manufacturing companies.

The reason for this is twofold. Firstly, to remain competitive, equipment manufacturers cannot only focus on developing equipment that performs well initially. Instead, they must develop equipment that performs well over its whole life cycle. Effective and efficient maintenance plays a vital role in achieving that (Alsyuf, 2007). Secondly, equipment manufacturers are searching for new business activities in which they take over the maintenance from their customers or provide solutions in which maintenance services are integrated parts of their offerings to the customers (Cohen et al., 2006; Neely, 2011). That makes equipment manufacturers responsible for the development of the maintenance service as well.

These trends have motivated equipment manufacturers to develop the capability of addressing maintenance and other service elements in their product development projects (Ulag & Reinartz, 2011). To develop competitive solutions, the literature proposes to apply approaches in which the equipment design and service elements are addressed in an integrated way (Baines et al., 2007; Meier et al., 2010). For further development of such approaches a deep understanding is required on both the interrelations between product and services, and the design activities in which they are addressed.

This thesis focuses on the maintenance aspects in industrial equipment development projects. The goal of the research is to support developers in addressing these maintenance aspects. This thesis presents the results of a design research study that is conducted to develop an overview of the aspects that are relevant to address and to propose how these aspects can be addressed successfully. Based on the results also three types of design support are proposed. Within the study, experts from three companies are involved. The current chapter gives an introduction to industrial equipment and maintenance in Section 1.1. The research topic is further introduced in Sections 1.2 and 1.3 by elaborating on the changing business activities and by explaining product development, respectively. Subsequently, Section 1.4 presents the research challenges in the field and the motivation for the research presented in this thesis. Section 1.5 introduces the research goal and Section 1.6 describes the research approach and the research questions. Section 1.7 presents the contributions of the research and, finally, Section 1.8 shows the structure of the thesis.

1.1 Industrial equipment and maintenance

The research targets industrial equipment. In particular, it focuses on the development of equipment used in production systems. As the classification presented in Figure 1.1 shows, such systems are static, concentrated, specific technical systems. Often the term capital good is used to refer to such a system. In this thesis, I use the terms *industrial equipment* and *equipment* interchangeably for it.

Type of technical system	Transportable		Static		
	Portable	Mobile	Distributed		Concentrated
			Network	Standard	
Examples technical system	Consumer and professional goods	Aircrafts, ships, trains	Roads, canals, distribution systems	HVAC systems, rotary equipment	Production systems, buildings
Typical maintenance providers	Service centres	Maintenance facilities	Mobile maintenance teams	Field services, mobile technicians, OEMs	Engineering and maintenance departments
	OEMs, engineering-, construction, maintenance contractors				

Figure 1.1: Classification of technical systems and their typical maintenance providers (based on Smit, 2014, p. 38)

The life cycle of industrial equipment follows the model from ISO (2008) that is presented in Figure 1.2. It distinguishes seven phases. In the exploratory phase, the needs of the stakeholders are identified and ideas for solutions are explored. Next, in the concept phase, feasible concepts are developed and selected. Selected concepts are subsequently worked out to a complete design in the development phase. In the production phase, the equipment is manufactured or built. In the use phase, the system is used for producing products or delivering services. The support phase is shown in parallel to the use phase. Supporting services, such as maintenance, are provided to enable operation of the equipment. Finally, in the retirement phase the system is removed from operation.

Figure 1.2: Generic model of system life cycle phases (from ISO, 2008)

The duration of the use and support phases of industrial equipment may vary, depending on the type of system, from 10 to 40 years (NVDO, 2014). During this period, maintenance needs to be performed. Maintenance is required because all equipment wears and tears, degrades with age or use and eventually fails. When equipment fails, it is no longer capable of delivering the products and services it is meant for. In the European Standard, maintenance is defined as “the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” (CEN, 2010, p. 5). Typical technical maintenance actions are cleaning, inspections, tests, monitoring, fault diagnosis, repairs, replacements and function check-outs. Examples of administrative and managerial actions are maintenance task preparation and maintenance scheduling. In the past, maintenance actions were mostly associated with actions performed on mechanical and electronic components. For the systems that are developed nowadays, maintenance is also required for software elements. Special categories of maintenance activities are modifications and overhauls. They have the purpose to adapt the equipment to functional demands and/or new legislation, so that the economic life time of the system is extended and investments in new equipment can be postponed.

The main objectives of maintenance are (based on CEN, 2010, p. 4):

- Ensuring the availability of a system to function as required.
- Upholding the quality of the products produced or of the service provided.
- Upholding the durability of the system and guaranteeing safe operation.

Two types of maintenance are distinguished: preventive maintenance and corrective maintenance. Preventive maintenance is maintenance aimed at reducing the probability of failure and the degradation of the equipment. Corrective maintenance is maintenance carried out when a fault is recognized and it is intended to get a system up-and-running again as quickly as possible. Maintenance is required to ensure that the equipment's primary process can be fulfilled, but it also leads to costs. Costs arise in different ways:

- Direct costs in the form of expenditures on resources that are necessary to perform the maintenance activities, such as personnel, tools, facilities, spare parts and management.
- Indirect costs that lead to a loss of revenues or reputation damage of the company:
 - Loss of production capacity when maintenance activities need to be performed. These costs are known under the term downtime costs. Especially unforeseen corrective maintenance is undesired, because it interrupts the primary process and could lead to disruptions of other related processes of the company, its suppliers and its customers.
 - Decrease of product quality if insufficient or improper maintenance is performed.

Because the costs of maintenance can be considerably high, users of industrial equipment try to search for a good balance between the direct plus indirect costs made for preventive maintenance and the direct plus indirect costs for corrective maintenance that can be avoided by performing preventive maintenance. During the use and support life cycle phases of the equipment, this can be done through the development and optimization of maintenance strategies. However, the need for maintenance, the necessary resources and the time that is required for performing maintenance, is already largely determined by the design of the equipment. Therefore, addressing the maintenance aspects during the development of industrial equipment, the topic of this thesis, is of key importance to obtain equipment with which good performance can be achieved during the use and support life cycle phases.

1.2 Changing business activities of equipment manufacturers

Addressing maintenance aspects during the development of equipment is even more important for equipment manufacturers due to their changing business activities of equipment manufacturers. Traditionally, equipment manufacturers focus on developing, producing and marketing physical products. They develop different types of equipment and engineer them for specific customer situations. Maintenance on the equipment is, as Figure 1.1 indicates, typically performed and managed by engineering and maintenance departments of the user. It may be backed-up by equipment manufacturers and maintenance contractors. However, this division of roles has changed. Trends show that the role of equipment manufacturers in performing and managing the maintenance activities has become larger (Cohen et al., 2006; Neely, 2011). Equipment manufacturers set up new business models in which they generate revenues both by offering maintenance services and by integrating services into their offerings to the customer.

Figure 1.3: Illustration of possibilities of roles that different parties can have in delivering equipment and maintenance related services

Figure 1.4 presents an overview of the different services that equipment manufacturers provide. These services vary from product-oriented services, such as the delivery of spare parts, to services in which the complete maintenance or operation function is taken over from the customer. As illustrated in Figure 1.3, nowadays equipment manufacturers provide many different solutions to individual customers. The rationales behind the trend that equipment manufacturers increasingly offer services and integrate services into their offering, can be categorized, according to Baines et al. (2009), into three sets of drivers:

1. Financial drivers; services can generate higher profit margins in comparison with offering physical products alone and they provide stability of income.
2. Strategic drivers; the use of service elements to differentiate the manufacturing offerings to gain a competitive advantage.
3. Marketing drivers; the use of services for selling more products, by using the services to influence the purchasing decisions of customers and to create customer loyalty.

Manufacturing companies find themselves in a unique position for offering competitive services. In comparison with other service providers, manufacturers own unique resources, among which installed base product usage and process data, product development and manufacturing assets, product sales forces and distribution networks, and field service organizations are the most critical (Uлага & Reinartz, 2011). Uлага & Reinartz (2011) identify five capabilities that manufacturers should build to exploit their advantages fully. One of them is developing their distinctive “design-to-service capability”. It comprises the incorporation of service elements early in innovation processes in such a way that physical product features and services elements interact synergistically for value creation, rather than in an additive manner. This could lead to new combinations of product and service offerings to the market, differentiation, and redesigns of current offerings so that delivery costs can be reduced.

	Product-oriented services	End-user's process-oriented services
Transaction-based services	<i>Basic installed base services</i> Documentation Transport to client Installation /commissioning Product-oriented training Hot line / help desk Inspection / diagnosis Repairs / spare parts Product updates / upgrades Refurbishing Recycling/ machinery brokering	<i>Professional services</i> Process-oriented engineering (tests, optimization, simulation) Process-oriented R&D Spare parts management Process-oriented training Business-oriented training Process-oriented consulting Business-oriented consulting
Relationship-based services	<i>Maintenance services</i> Preventive maintenance Condition monitoring Spare parts management Full maintenance contracts	<i>Operational services</i> Managing maintenance function Managing operations

Figure 1.4: Overview of services provided in the industrial equipment industry (from Oliva & Kallenberg, 2003, p. 168)

1.3 Product development

Product development is the complete process of bringing a product to the market. Ulrich & Eppinger (2012) extensively describe product development. They define it as the steps or activities that a company employs to transform an idea or a product concept into a physical product and to bring it to the market. A product development process consists of a number of successive stages. During these stages numerous iterations of development activities, such as concept generation, detail design of components and performance testing, take place. How development processes are exactly organized and which activities are performed, differs for individual companies and the products being developed.

Figure 1.5 represents a generic description of the development process of complex systems, such as automobiles, aircrafts and the industrial equipment targeted in the research. Typical for the development process of complex systems is that a number of system-level issues are addressed. The concept development stage considers the architecture of the entire system. In the system-level design stage, the system is decomposed into sub-systems and further into components. These are developed by a number of teams in parallel and in collaboration with a multitude of dependent and independent suppliers (see Figure 1.3). In the integrate and test stage, the components and sub-systems are integrated into the overall system.

To be successful, product development should result in products and services that can be produced and sold profitably. Ulrich & Eppinger (2012, pp. 2-3) specify five specific dimensions on which high performance is desired: product quality, product cost, development time, development cost and development capability. When a company achieves a high level of performance on all of these dimensions, it is likely that product development will lead to successful business. In order to improve the outcomes of product development, developers make decisions both on products being developed and on the development process itself (Reymen et al., 2006).

In a company, several functions contribute to product development, of which design, production and marketing are considered to be the core ones. These functions have their own typical tasks and responsibilities (see, for example, Ulrich & Eppinger, 2012, p. 14). Several other functions play key roles at particular points in the process. Among these other functions is the service function that has the task to identify the service issues that must be addressed. However, the service itself is, traditionally, developed as add-on to the product. Researchers argue that, to make successful development decisions, product development requires coordinated decision making that is driven by the intrinsic interdependencies among decisions to be made by the different functions (Holman et al., 2003; Krishnan & Ulrich, 2001). That is in line with the needs of companies to incorporate service elements early in their development process (see Section 1.2).

Recent literature on product development elaborates on this idea. It proposes to regard integrated solutions of products and services as a product/service systems (PSS) (Baines et al., 2007). The term industrial product/service system (IPS²) is also used for PSS in business-to-business environments (Meier et al., 2010). Approaches for developing PSSs focus, as illustrated in Figure 1.6, on the development of integrated products and services in such a way that revenues can be generated during the whole life cycle. The key idea behind PSS approaches is that a holistic, integrated view is required on products and services. Simply adding a service to the designed product is no longer considered to be sufficient. These approaches have potential to help companies develop competitive product and service solutions.

Figure 1.5: An illustration of the complex systems development process
(from Ulrich & Eppinger, 2012, p. 22)

1.4 Research motivation

Various literature, as is presented in Chapter 2, discuss which maintenance aspects should be addressed during the development of industrial equipment and how to do that. Concerning integrated development of product and service offerings, research is predominantly done within the context of the development of PSS and IPS². That research comprises a vast number of topics, varying from research into business models and contract forms, design and development of the product/services systems, and into their contribution to sustainability (Meier et al., 2010). Research that is conducted on the topic of design and development has identified various issues to be addressed for successful development of integrated offerings of products and services. Examples of issues are the integration between product design and service design (Sakao et al., 2011), feedback from the field (Sakao et al., 2011), linking information between products and service activities during the design phase (Meier et al., 2010) and the need for well-developed tools and methodologies (Baines et al., 2007). Addressing these issues is considered to be essential for successful development of integrated offerings of products and services. Also, research is conducted in the form of developing methods and tools that could support in developing PSS and IPS² offerings systematically. Vasantha et al. (2012) provide a review of these methods and tools.

Although research is available on the development of PSS an IPS², the research is considered to be still in its infancy. To further develop knowledge on this topic and to develop useful support, Baines et al. (2007) and Meier et al. (2010) argue that especially in-depth studies and research in practice are required. Such studies could create a deep understanding on the interrelations between products and services and could evaluate the proposed methods and tools in a real industrial context. The research of Tan et al. (2010) further indicates that there might be a gap between the proposed methods and tools in the literature and the practices in industry. Aurich et al. (2006) also underline that further research should be a systematic investigation of both the interrelations between products and technical services and the corresponding design activities.

Figure 1.6 Traditional product development versus the product/service-system approach for industrial equipment development (based on Tan, 2010, p. 12)

Figure 1.7: Intended effect of support

Figure 1.8: DRM framework (from Blessing & Chakrabarti, 2009, p. 15)

The necessity for research into practice to understand how integrated offerings of products and services can be developed and the importance of maintenance for good performance of industrial equipment over its whole life cycle, together form the main motivation for doing research on how maintenance aspects can be successfully addressed. The key assumption is, as also Meier et al. (2010) indicate, that industry already has its own approaches. Studying the approaches could help to get a deep understanding of the interrelations between equipment and maintenance service design and how they can be successfully addressed in practice.

1.5 Research goal

A research project has an external and internal research goal (Verschuren & Doorewaard, 2010, pp. 16-17). The external research goal represents the contribution that is made to solve a problem outside the research itself. The internal goal concerns the knowledge to be developed in order to achieve the external research goal and thus represents the scientific contribution of the research. The external and internal research goal are:

External research goal. To support developers in addressing maintenance aspects.

Internal research goal. To develop knowledge on the relevant maintenance aspects to be addressed in development projects, on how these aspects can be addressed successfully and on how developers can be supported to do this.

The external research goal follows from the need of companies to improve their capability of addressing maintenance and other service elements during their development activities, as discussed in Sections 1.1 and 1.2. Figure 1.7 illustrates how support should help developers in companies. Support should improve a company's capability in addressing the maintenance aspects, which should improve the quality of design decisions with respect to the maintenance aspects. Making better design decisions on maintenance aspects means that the maintenance performance of the equipment will be improved, which ultimately leads to equipment and service offerings that are more competitive. The internal research goal builds on the research motivation that is described in Section 1.4. Section 1.4 indicates that the literature does not yet provide a clear understanding of the interrelations between product and maintenance service elements, how they can be addressed successfully and how developers can be supported. Therefore, this research focuses on eliciting knowledge that experts in companies have on the research topic and on proposing models that represent this knowledge in a usable way.

1.6 Research approach and research questions

To structure the research, I apply a design research methodology. A design research methodology is a suitable method because the objectives of design research are similar to my objectives. Blessing & Chakrabarti (2009, p. 9) formulate the objective of design research as "the formulation and validation of models and theories about the phenomenon of design, as well as the development and validation of support founded on these models and theories, in order to improve design practice, management, education and their outcomes".

Examples of design-oriented research frameworks that can be used for design research are the design science research cycle by Van Aken & Romme (2009, p. 10), DRM by Blessing & Chakrabarti (2009) and the framework for design science by Wieringa (2014, p. 7). I have selected DRM, because it specifically focuses on the development of design support tools and proposes the research stages that are required to develop the support profoundly. The other frameworks are more general frameworks that focus on the design of solution-oriented knowledge. Also, the DRM framework explicitly provides the possibility to select the research

stages on which the research will be focused. Depending on the existing knowledge, the research can focus on the development of understanding, the design of support tools or the evaluation of support tools.

The DRM framework is depicted in Figure 1.8. It contains four stages: Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II.

The *Research Clarification* stage aims at finding evidence or indications that support the assumptions in order to formulate a realistic and worthwhile research goal.

The *Descriptive Study I* stage intends to make a description of the existing situation. The description must be detailed enough to determine which factor(s) should be improved to improve the development process. The outcome of this stage is a better understanding of the existing situation.

In the *Prescriptive Study* stage the increased understanding of the existing situation is used to improve one or more factor(s) by introducing some kind of support.

The *Descriptive Study II* stage has the objective to evaluate the support on its applicability, usability and its usefulness for improving the identified factors during the Descriptive Study I stage.

Blessing & Chakrabarti (2009, p. 18) propose seven types of research projects that can be performed within the DRM framework. Table 1.1 shows these types and their main focus. Depending on the state of the art, the researcher needs to decide whether a comprehensive study is required with respect to a particular stage or that a review-based study is sufficient.

Research type	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1	Review-based	Comprehensive		
2	Review-based	Comprehensive	Initial	
3	Review-based	Review-based	Comprehensive	Initial
4	Review-based	Review-based	Review-based Initial/Comprehensive	Comprehensive
5	Review-based	Comprehensive	Comprehensive	Initial
6	Review-based	Review-based	Comprehensive	Comprehensive
7	Review-based	Comprehensive	Comprehensive	Comprehensive

Table 1.1: Types of possible research projects within the DRM framework and their main focus (from Blessing & Chakrabarti, 2009, p. 18)

Blessing & Chakrabarti (2009, pp. 18-19) also indicate to take into account the time that is available for a research project when selecting a research type. They indicate that research projects which focus on only one particular stage, thus Types 1 to 4, are very suitable for PhD projects. The other types are considered to be more suitable for the work of research groups or when a problem with a very specific scope is addressed. The research described in this thesis is a Type 2 project. It thus contains the Research Clarification, a *comprehensive* Descriptive Study 1 and an *initial* Prescriptive Study. An initial Prescriptive Study is a study that, at least, suggests how the findings of Descriptive Study I can be used to improve design (Blessing & Chakrabarti, 2009, p. 19).

The results of the Research Clarification are described in the current chapter. To guide the research related to Descriptive Study I and the Prescriptive Study, four research questions are formulated:

RQ1. What is the relevance of addressing maintenance aspects in industrial equipment development projects?

RQ2. What are the relevant maintenance aspects to be addressed in industrial equipment development projects?

RQ3. How can maintenance aspects be addressed in industrial equipment development projects and what factors affect whether this is successfully done?

RQ4. How can developers be supported in successfully addressing maintenance aspects in industrial equipment development projects?

RQ1, RQ2 and RQ3 guide Descriptive Study I and RQ4 guides the Prescriptive Study.

Descriptive Study I includes a literature study and an empirical study in which experts from three Dutch companies are involved. The empirical study is of a qualitative nature and the main methods used are interviews and validation sessions. The empirical study is further introduced in Chapter 3. Within Descriptive Study I, RQ1 addresses the question why companies that provide industrial equipment have the need to address maintenance aspects. This research question is meant to verify that addressing the maintenance aspects is relevant for the involved companies in the research and to provide context for understanding the results of the other questions. RQ2 and RQ3 together concern the development of an understanding of the relevant maintenance aspects and of how maintenance aspects can be addressed in practice. The answers to these questions should provide insight into the aspects that experts consider to be relevant to address, the activities that developers undertake to address maintenance aspects and the factors that affect whether that is successfully done. It is the purpose to use these insights to provide generic answers to the research question in which overviews are provided across the involved companies. It is not the purpose to make comparisons between the companies.

The research within the Prescriptive Study mainly concerns logical reasoning. The results of Descriptive Study I are taken as starting point and used to propose three types of support for developers. RQ4, which guides the Prescriptive Study, concerns the development of possible support that can help developers in addressing maintenance aspects, which is the goal of the research.

1.7 Contribution

The main scientific contribution of the research is that it makes the implicit knowledge of developers in practice explicit and that it organizes this knowledge in models that enable it to be used as design support. The answers to the research questions, provided in Chapters 3 to 6, together give a holistic overview on the relevant maintenance aspects in industrial equipment development projects, how they can be addressed successfully and how developers can be supported. Below, I give a more detailed description of the contribution related to each research question:

RQ1 Empirical evidence for the relevance of addressing maintenance aspects in industrial equipment development projects and specific reasons why companies want to improve on addressing them.

- RQ2 A model of the relevant maintenance aspects and an explanation of their importance during equipment development projects. The model gives an overview of aspects related to the design of the equipment and the design of the maintenance service that together affect the maintenance performance of the developed systems and orders the aspects in a logical way. The model also shows the interrelations between the equipment and maintenance service design and the interrelations with elements of the environment in which the equipment is used.
- RQ3 An overview of the activities that developers perform to address maintenance aspects and an overview of factors that affect whether these activities are successfully performed, including descriptions. The descriptions explain the activities and factors in more detail.
- RQ4 Insights obtained from Descriptive Study I on which support is useful for practitioners to improve on addressing maintenance aspects; and three concrete examples of such support: (1) the use of the model and overviews developed to answer RQ2 and RQ3, as they are presented in such a way that they can also be used for decision making in development projects in practice, (2) a maintenance performance calculation tool and (3) a set of design-for-maintenance guidelines.

1.8 Outline of the thesis

The outline of this thesis is presented in Figure 1.9. This first chapter has introduced the research topic and research approach. Chapters 2 to 5 present the results of the Descriptive Study I. Chapter 2 gives an overview of the literature that discusses maintenance aspects and how they can be addressed. Chapter 3 firstly introduces the empirical study that is performed and the approach that is followed for conducting it. Secondly, Chapter 3 presents the findings of the empirical study related to RQ1, and thus discusses the relevance of addressing maintenance aspects for the three involved companies. Chapters 4 and 5 present the findings of the empirical study with respect to RQ2 and RQ3, respectively. These chapters thus discuss which maintenance aspects are relevant to address and how these aspects can be successfully addressed in development projects. The chapters present and structure the knowledge that is retrieved from experts at the three involved companies. Subsequently, Chapter 6 presents the findings of the Prescriptive Study and thus answers RQ4. It discusses the insights that the Descriptive Study I gives on which support could be useful for developers and it presents three concrete tools to support addressing maintenance aspects. Finally, Chapter 7 concludes the research by presenting the key findings, discussing the used research approach and giving recommendations for further research.

Figure 1.9: Overview of the thesis

2 State of the art literature on addressing maintenance aspects

This chapter presents an analysis of the state of the art literature on addressing maintenance aspects in development projects. The goal of the analysis is to present the existing knowledge with respect to the research topic and to identify the potential areas for further development of the literature. The analysis of the literature focuses on Research Questions 2 and 3, as they are the main research questions to be answered for Descriptive Study I. No comprehensive literature study is performed for the Prescriptive Study, because it is out of the scope of the research goals in an *initial* Prescriptive Study (see Section 1.5). However, the results with respect to RQ3 also include literature that refers to methods and tools that can be used to support developers. This literature gives an indication of the support that is available.

For the construction of this literature overview, I have searched for literature that considers the maintenance aspects from a product development perspective. This is the relevant perspective with respect to the goal of the research to support developers. Specifically, I have searched for literature that is both related to maintenance aspects and product development, which is depicted in Figure 2.1. To find relevant literature, I have conducted internet searches through Google Scholar. For these internet searches, I combined key words related to maintenance aspects with key words related to product development. Examples of key words related to maintenance aspects are “maintenance”, “maintenance aspects”, “service aspects”, “maintainability” and “serviceability”. Examples of key words related to product development are “product development”, “design”, “product design”, “system design”, “product/service system development”. However, most of the relevant literature is found through references in papers and books.

Figure 2.1: Illustration of the literature that is considered to be relevant for the literature overview

The papers and books that I have selected for the overview in this chapter meet the criterion that they provide overviews with respect to relevant maintenance aspects (Section 2.1), how they can be addressed (Section 2.2.1) or the factors that affect whether that is successfully done (Section 2.2.2). Literature that only discusses, for example, one particular aspect or discusses a specific method that can be used to address maintenance aspects, is not included. Such literature is too specifically focused on single aspects or methods to be useful to construct a generic answer to the research questions. With respect to the literature about relevant maintenance aspects, the focus lies on literature that discusses aspects that developers can influence directly when developing products and/or related services. I do not discuss the literature that only addresses the high level

performance goals that are affected by addressing such aspects, like the production quality, system availability and lifecycle costs. As discussed in Section 1.2, improving the performance of industrial equipment on such indicators is the ultimate goal of addressing maintenance aspects. However, a more detailed level of aspects needs to be considered when affecting these indicators through the design of the equipment and/or service. For example, if a developer tries to position components that regularly need maintenance at easily accessible locations, the developer does so to decrease the time to maintain and/or the direct maintenance costs related to these components. Such design efforts can indirectly lead to a higher availability and lower life cycle costs.

This chapter is structured as follows. Section 2.1 discusses relevant literature that gives insights into the maintenance aspects that are important to consider in development projects. This is the topic of RQ2. Section 2.2 deals with relevant literature on how maintenance aspects can be addressed and what affects whether that is done successfully: the topic of RQ3. Section 2.3 presents the conclusion.

2.1 State of the art on relevant maintenance aspects

A vast literature is available on aspects that are important to address in development projects with respect to the maintenance of a product or a system. The literature mainly stems from the fields of (1) product design and engineering, (2) systems engineering and (3) product/service system development. In Sections 2.1.1, 2.1.2 and 2.1.3, I summarize the relevant insights from the state of the art in these fields. Next, Section 2.1.4 discusses research from Markeset & Kumar (2003a), which provides relevant insights on the basis of an empirical study in industry. I discuss this paper separately, since it does not fit one of the aforementioned fields only. Instead, it is the only paper that is found which elaborately discusses, from the perspective of a company, what the relevant aspects are and what approaches can be used to address them. Finally, Section 2.1.5 provides the conclusion on this part of the state of the art literature.

2.1.1 Aspects from the literature on product design and engineering

The literature on product design and engineering dealing with maintenance focuses on how, through design, maintenance can be made unnecessary or substantially reduced and on how maintenance can be made easy, quick and cheap to perform. *Reliability* and *Maintainability* are considered as the relevant product properties to enhance. *Reliability* is the ability of a product to perform a required function under given conditions for a given time interval without any substantial or functional failure (CEN, 2010, p. 7). *Maintainability* is the ability of a product under given conditions of use, to be retained in, or be restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and recourses (CEN, 2010, p. 7). Reliability and maintainability are so-called *relational properties*: properties of interest for the users that they perceive when they use the product (Andreasen et al., 2015, p. 317). When such properties are addressed, not only aspects that are related to the products must be considered. They must be addressed together with the conditions, processes and other contextual elements in which the product is used. The model of Hubka & Eder (1984), presented in Figure 2.2, shows how relational properties (indicated in the figure with “external properties of machine systems”) depend on a product’s “elementary” and “general design properties”. The elementary design properties are the only attributes that a developer can determine directly.

Figure 2.2: Model of the relationships between different product attributes, focused on mechanical design; the attributes with which reliability and maintainability are interrelated are marked (from Hubka & Eder, 1984, p. 145; the marking is added)

The marking in the figure shows which elementary design properties and general design properties affect a product's reliability and maintainability. Also, it shows that the other external properties with which reliability and maintainability are interrelated.

The literature in the field of product design and engineering provides design principles for the design of equipment with respect to reliability and maintainability. Thompson (1999) addresses principles for equipment design with respect to reliability and maintainability. More specifically, Thompson (1999, pp. 135-156) addresses general principles on: simplicity and elegance; minimum number of parts; modular construction; accessibility; sensibly sized components; adjustments; moving parts; and in detail with respect to reliability, the strength of components and assemblies and the loads applied to them. Dhillon (1999, pp. 82-97) provides a comprehensive overview of attributes and guidelines to be addressed with respect to maintainability. Dhillon (1999) categorizes them under the following main topics: standardization; interchangeability; modularization; simplification; accessibility; identification; accessibility and identification checklists; and general maintainability design guidelines and common maintainability design errors.

Pahl et al. (2007, pp. 385-388) discuss *design for maintenance*. They address the effect of the equipment design on the maintenance strategy (failure repair or preventive repair determined by either interval or condition), the need for service measures and how the execution of service can be facilitated. They also explicitly refer to safety, ergonomics and assembly principles, as maintenance is related to them.

Authors that specifically indicate the related process and contextual elements are Wani & Gahndhi (1999) and Coulibaly et al. (2008). Wani & Gahndhi (1999) categorize the attributes of importance into design attributes, personnel and logistic support:

- Design attributes: accessibility; disassembly/assembly; standardization; simplicity; identification; diagnosability; modularization; and tribo-concepts.
- Personnel: personnel including ergonomics; and system environment.
- Logistic support: tools and test equipment; and documentation.

Coulibaly et al. (2008) classify maintainability criteria into intrinsic and contextual criteria:

- Intrinsic criteria: repairability; accessibility; assemblability; disassemblability; standardization; interchangeability; survivability; and redundancy.
- Contextual criteria: competencies; tooling; logistics; environment; detectability; testability; maneuverability; and auto diagnostic.

Both Wani & Gahndhi (1999) and Coulibaly et al. (2008) use the attributes for the development of models to assess the maintainability of products.

2.1.2 Aspects from the literature on systems engineering

Literature in the field of systems engineering describes from a system perspective which support elements must be considered during system development processes. A comprehensive work in this field is Blanchard & Fabrycky (2014). The basic idea in this field is that all elements of a system should be considered on an integrated basis from the beginning and throughout the whole development process (Blanchard & Fabrycky, 2014, p. 76). With respect to the integration of maintenance and support in the development process, Blanchard & Fabrycky (2014, p. 76) state that “the prime system elements must be designed in such a way that they can be effectively and efficiently supported through the entire system life cycle and the maintenance and support infrastructure must be responsive to this requirement”. According to them, developers must address the characteristics of the equipment design related to the maintenance and support system and must develop the maintenance and support concept. The important aspects to be addressed, are:

- With respect to the equipment design: reliability, maintainability, human factors and safety; constructability and producibility; supportability; sustainability; disposability; and related requirements for design.
- With respect to the maintenance and support concept: repair policies; organization responsibilities; maintenance support elements; effectiveness requirements; and environment.

For details on these aspects, I refer to Blanchard & Fabrycky (2014) and to Jones (2007). Jones (2007) elaborately discusses supportability.

With respect to software elements, which are nowadays integrated parts in industrial equipment, the International Standard (ISO, 2011) gives, from a system perspective, definitions for reliability and maintainability and the characteristics that affect them. The characteristics are:

- Reliability: maturity, availability, fault tolerance and recoverability.
- Maintainability: modularity, reusability, analyzability, modifiability and testability.

With respect to software, Jones (2007, p. 11.19) mentions software standardization as an extremely important issue in order to realize cost-effective support.

Smets et al. (2012) provide a holistic Design for availability framework. The framework presents aspects that can be addressed and methods that can be used to identify possibilities to cost-effectively optimize the availability of capital goods. The aspects and methods are categorized

into seven categories, namely: system reliability, fault discovery, disassembly, maintenance actions, spare/repair packages, reliability-centred maintenance and commercial and technical support. Within the framework, the categories are related to three maintenance performance indicators: the mean time to failure, the mean time to support and the mean time to repair.

2.1.3 Aspects from the literature on product/service system development

Literature in the field of product/service systems (PSS) and industrial product/service systems (IPS²) development focuses on the development of solutions that provide value to the customer and consist of both product and service elements. The relevant aspects to be addressed do not only concern the design of the physical artefacts in a solution, but also include the business model, service activities, the PSS/IPS² life cycle, the aspects of the system's context, resources to deliver value and the relations among them (Meier et al., 2010). The delivery of maintenance can be one of the service elements in a PSS to provide value to the user. Roy et al. (2013) give an overview of themes that emerge related to the enhancement of maintenance activities in IPS² projects. These themes are related to both technological and organizational development. They are:

- Technological themes: standardization of, for example, quality of diagnostic systems and data; application of advanced information technology; using the maintenance strategy for optimizing the life cycle of the equipment; autonomous maintenance; and degradation at component and system level.
- Organizational themes: designing the skillset to deliver the maintenance solution; structuring the organization to meet the requirements; maintaining safety; and organizing the supply chain.

For the IPS² provider these themes are important because the maintenance service can be a major driver of the whole life cost when solutions are offered in which the performance of the equipment is guaranteed for a long period.

2.1.4 Relevant aspects from research by Markeset & Kumar (2003a)

Markeset & Kumar (2003a) provide insights into how product design, product support and product exploitation influence each other and how they should be addressed in development projects of industrial systems. They do that based on an empirical study conducted in a manufacturing company that “produces various types of customized, integrated and advanced production systems” and provide the model that is depicted in Figure 2.5. They discuss that aspects related to both the product and the product support must be addressed and decisions on them must be made by considering the environment in which the product is used, i.e. the product exploitation. Specific aspects related to the product and support to be addressed in the development project, are:

- Product characteristics:
 - Reliability: time; costs; and available state of the art technology.
 - Maintainability: easy accessibility; easy serviceability; easy interchangeability; and modularization.
- Product support: installation and commissioning; spare parts; upgrading and modifications; warranty schemes; training; documentation; online and help-line support; remote monitoring and surveillance.

Figure 2.3: “Design out maintenance” (from Markeset & Kumar, 2003a, p. 385)

Figure 2.4: “Design for maintenance and product support” (from Markeset & Kumar, 2003a, p. 386)

Figure 2.5: Model of the relationships between product characteristics, product support and product exploitation (from Markeset & Kumar, 2003a, p. 383)

Markeset & Kumar (2003a) also describe the main approaches that developers can apply when considering maintenance in design: “design out maintenance” and “design for maintenance and product support”. These are illustrated in, respectively, Figure 2.3 and 2.4.

“Design out maintenance” comprises that developers identify the product characteristics that could cause maintenance costs and try to eliminate them. When doing this, developers need to consider the costs of guaranteeing the reliability of the product during the life cycle, the costs of available state of the art technology and possible other considerations, such as the product capacity and design alternatives. Trade-offs between the benefits and the costs of eliminating maintenance can be made by means of life cycle cost analysis. “Design for maintenance and product support” comprises the design of a compensating maintenance strategy to reduce risks and to make the product easy and cheaper to maintain and support. This approach is preferred when the life cycle costs of the product design in which maintenance is eliminated are higher than when a design for maintenance and product support approach is applied. To determine if that is the case, developers need to consider issues such as the accessibility, interchangeability of parts, use of modular systems and the elements of the product support to be developed.

2.1.5 Conclusion

This section shows that different fields of literature discuss which maintenance aspects are important to address in industrial equipment development projects. Aspects that are discussed in the literature are related to the product, product support and the elements to be developed for maintenance delivery services. Aspects related to the product and the product support are elaborately discussed. What the literature does not provide, is a clear overview of the elements to be developed for the maintenance delivery services and their interrelations with the aspects in the other categories. Those aspects become especially relevant for PSS/IPS² development. Therefore, a potential area for further development of the literature is the integration of knowledge from the fields of product design and engineering and systems engineering into the field of PSS/IPS² development. As also Maussang et al. (2009) indicate, for PSS development, developers must carefully consider the interactions between the physical objects and service elements, but also need to specify engineering criteria for the product elements to be developed.

2.2 State of the art on how to address maintenance aspects

This section discusses the relevant literature with respect to the question how maintenance can be addressed successfully. The relevant literature can be divided into two groups: (1) literature that discusses activities and approaches on how to address such aspects in development projects and (2) literature that discusses the organizational factors related to addressing such aspects. I discuss the insights from the state of the art literature on these two groups in Sections 2.2.1 and 2.2.2, respectively. Section 2.2.3 shows the conclusions on this part of the state of the art literature.

2.2.1 Activities and approaches to address maintenance aspects

Blanchard & Fabrycky (2014) prescribe the activities throughout the whole life of a system in which reliability, maintainability and supportability should be addressed. Appendix 1 shows the complete overview.

Summarized, these activities are the following:

- Conceptual design: requirements definition and planning; and development of the maintenance concept.
- Preliminary design: allocation of requirements; analysis and trade-offs; maintenance engineering analysis; design support; performance predictions; and design reviews and approvals.
- Detail design and development: analysis and trade-offs; maintenance engineering analysis; design support; performance predictions; performance demonstrations; provisioning and acquisition of logistic support elements; test and evaluation of logistic support capability; and design reviews and approvals.
- Production/construction: test and evaluation; data collection and analysis; acquisition of logistic support elements; test and evaluation of logistic support capability; and corrective improvement actions;
- System utilization and life cycle support: provisioning and acquisition of logistic support elements, data collection, analysis and evaluation; and system modification.

An essential element of addressing reliability, maintainability and supportability is the feedback from the activities in each phase on the design of the product, on the maintenance concept and on the design process.

Takata et al. (2004) also indicate that maintenance is something that should be addressed over the whole life cycle. They argue that maintenance involves the following six activities:

1. Maintainability design
2. Maintenance strategy planning
3. Maintenance task control
4. Evaluation of maintenance results
5. Improvement of maintenance and products
6. Dismantling planning and execution

According to Takata et al. (2004), maintenance strategy planning plays a key role. It involves the selection of an appropriate strategy for maintenance among various options, such as breakdown maintenance, time-based maintenance and condition-based maintenance.

In addition, they emphasize that three issues should be considered in order to manage these activities effectively throughout the life cycle, namely: (1) adaptation to various changes during the life cycle, (2) continuous improvement of the product and (3) integration of maintenance information.

Within the context of the PSS development, Tan et al. (2010) provide an overview of the most relevant design approaches related to the service aspects of products. They distinguish four categories of approaches:

- Design for maintainability/serviceability approaches: approaches that cover the support of repair and maintenance activities on the product. Three examples of such approaches are (1) the application of design principles for reliability and maintainability, similar to the ones that are discussed in Section 2.1.1, (2) the approach of Takata et al. (2004) which is discussed above and (3) analysis methods and tools to assure safety of operation and reliability of technical systems. Examples of the latter are Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA). I refer to Mital et al. (2006, pp. 179-239) for a comprehensive overview of design for maintainability/serviceability approaches.
- Design for supportability approaches: approaches that cover all product supporting activities that include, besides repair and maintenance, also elements of the support system, such as training, spare parts and documentation.
- Design for service approaches: approaches that focus on designing the service first, before the product. Typical of such approaches is that design specifications are defined in terms of customer activity performance and not just the product performance. The approach of Harrison (2006) is mentioned as an example.
- Service design approaches: approaches in which the object being designed, is a process or activity and not a physical artefact. An example is the methodology by Vandermerwe (2000) that focuses on the activities that customers go through to get the benefits of the offered product and services.

Tan et al. (2010) also map the approaches to the different types of services to be developed. They consider design for maintainability/serviceability and design for supportability approaches as the basic for the development for merely product-oriented services (see Figure 1.4). Design for service and service design approaches become relevant when the company also offers the more customer-oriented services. Tan et al. (2010) indicate that design for service approaches represent the current state of the art in PSS design in manufacturing firms. Regarding service design approaches, they point out that services are rarely seen as a design object, but that companies refer to it as new business development.

Various authors propose methodologies for PSS design. Vasantha et al. (2012) provide an overview of state of the art PSS methodologies and evaluate the current level of maturity of eight of them. However, these are methodologies that are still in their initial stages of development and that are not applied in practice. Vasantha et al. (2013) propose a framework for PSS development that has the potential to be used, according to its evaluation in industry. In contrast to other methodologies, it uses an existing system as starting point and elicits the customer's needs from the deficiencies in that system. The framework facilitates the exploration of a wide variety of PSS designs. Its potential lies, among others, in supporting the development of PSS designs from a holistic systems approach by facilitating a change in the developers' mindset from a product-centric one to a system-centric one.

Level of maturity	Foote (2013) Focus on Reliability and maintainability (R&M)	Goffin (2000) Focus on Supportability	Rapacini (2013) Focus on New service development (NSD)
1 – Initial; ad hoc efforts	R&M may be recognized as an important product attribute, but no formal program exists.	Support is not recognized and there is no evaluation of support requirements during the design stage.	NSD Projects are run ad hoc and as chaotic initiatives. There is no stable environment to support NSD. Outcomes depend on individual competences of people.
2 – Repeatable; disciplined effort	R&M is recognized as an important product attribute and a repeatable program is used.	Design for supportability goals focus on reliability and ease-of-repair. Broader aspects of support are not considered.	NSD Projects are not carried out according to established guidelines. There is no common understanding on how a service should be designed and engineered. Few lessons learned of past projects are repeated. A systematic perspective is lacking.
3 – Defined; standards and consistency	The R&M program is documented and has been incorporated in the company's overall systems engineering process.	Full involvement of field support specialist in new product development reviews, but too late in the development cycle to be implemented.	NSD projects are planned and run according to documented and approved schemes. Key competences for successfully NSD are not totally exploited. Outcomes of NSD project are not predictable.
4 – Managed; predicted effort	Quantitative goals and requirements are set for all products. Achievement of R&M is tracked and the results are included as lessons learned.	Quantitative goals are set for all aspects of support. Cost models are used to guide design decisions which may need to be made about trade-offs between features, manufacturability and supportability.	NSD projects are systematically managed and controlled. There is commitment from management and investments made in service engineering methods. Predictable results can be achieved, but may be insufficient to achieve the established objectives.
5 – Optimized; continuous improvement	Feedback from each product development and manufacturing effort is used to identify strengths and weaknesses of the R&M program, with the goal of continual improvement.	Financial reporting mechanisms are used to ensure that return on design-for-supportability investments are visible to the management.	The NSD process is continually improved, through full understanding of the relationships among the elements constituting the process. There is an explicit strategy to improve NSD performance through incremental and/or radical innovation of processes, technologies and resources.

Table 2.1: Characteristics of the evolutionary stages that companies go through with respect to addressing reliability and maintainability, supportability and new service development (based on Foote, 2013; Goffin, 2000; Rapaccini et al., 2013)

2.2.2 Organizational factors related to addressing maintenance aspects

There is little research on how companies integrate addressing maintenance and related aspects in their development processes. The most elaborate work is the research of Markeset & Kumar (2003b). They give a comprehensive description of how a manufacturing company integrates Reliability, Availability, Maintainability and Supportability (RAMS) and risk analysis in its design, development and manufacturing processes. Also, they extensively describe the organizational elements to be considered in order to get an optimal result. Examples are the training of employees and the coordination between work processes, tools and information sources.

Foote (2013), Goffin (2000) and Rapaccini et al. (2013) describe the evolutionary stages that companies go through when improving on addressing reliability and maintainability, supportability and new service development, respectively. With respect to the latter, new service development refers to the development of product-centric PSSs; PSSs built around the provision of products. Table 2.1 shows the stages, which are indicated as the level of maturity, and the characteristics of the development processes that belong to each stage. The levels of maturity range from initial, and ad hoc efforts, to a level at which a company continuously improves its activities. The basic idea behind the maturity levels is that higher levels represent an increased capability in managing the specific area.

Rapaccini et al. (2013) also indicate the specific elements on which the maturity should be assessed. These can be seen as the elements on which a company should improve to become better in addressing the aspects and thus to reach a higher level of maturity. Table 2.2 shows these elements together with the factors identified by Antioco et al. (2008), Goffin & New (2001), Markeset & Kumar (2003b) and Tan et al. (2010), that affect how successfully maintenance-related aspects are addressed.

2.2.3 Conclusion

This section shows the literature that addresses how maintenance aspects can be addressed in development projects. Also, it shows that a variety of factors affect whether that is successfully done. Addressing maintenance aspects should be done throughout the whole life cycle of a system in various development activities. During these development activities, both the product and the maintenance concept should be developed.

The literature provides a range of methodologies that could be used to address maintenance aspects; especially, it provides approaches that are meant for supporting decision making on product related aspects. When it comes to approaches in which also service elements are considered as a design object, the literature indicates that these approaches are still in their initial stage of development.

Little literature is available on how addressing maintenance aspects is implemented in development processes in practice. The available literature shows that companies go through evolutionary stages when improving their capability in addressing maintenance related aspects. Numerous organizational factors affect whether or not they are addressed successfully. The gap in the literature concerns the lack of a deep understanding of the practices of developers in companies, and what support could help them to improve on addressing the maintenance aspects.

Source	Elements of importance
Antioco et al. (2008)	<p><i>Type of research: empirical research to identify organizational and communication factors that affect relative product and service characteristics.</i></p> <p>Important courses of action for manufacturing companies are related to the following three topics:</p> <ul style="list-style-type: none"> - Managing service feedback. - Information-sharing norms. - Communication channel and content.
Goffin & New (2001)	<p><i>Type of research: empirical study on how to address customer support in new product development.</i></p> <p>Identified best practices for addressing customer support in new product development are:</p> <ul style="list-style-type: none"> - Closely involving customer support experts in new product development. - Performing a comprehensive evaluation of support needs at the design stage and setting suitable design goals. - Using data management systems to monitor all aspects of field support. - Having top management that recognizes the importance of customer support. - Using customer support to gain a competitive advantage and to increase revenues.
Markeset & Kumar (2003b)	<p><i>Type of research: empirical study on the integration of reliability, availability, maintainability and supportability (RAMS) and risk analysis in the work processes of a manufacturing company.</i></p> <p>Element of the RAMS integration process are:</p> <ul style="list-style-type: none"> - RAMS, LCC and risk analysis tools and methods. - RAMS and risk analysis information and data. - Data bases and information systems. - Organizational management and support. - Motivation, cooperation, teamwork, knowledge, creativity and innovation. - Communication and interface with customers, suppliers and distributors. - Product characteristic evaluation. - Project management and control. - Quality assurance and control.
Rapaccini et al. (2013)	<p><i>Type of research: empirical research to develop a model to assess the maturity of new service development (NSD) processes</i></p> <p>The areas of importance to assess a company's maturity on NSD and their elements are:</p> <ul style="list-style-type: none"> - Organizational approach: relevance of NSD; roles; and management practices. - Resources: budget; tools and methods; skills. - Customers, suppliers and other stakeholders: customers; suppliers and other stakeholders. - Performance management: feedback systems (satisfaction, acceptance and impact of new services); and key performance indicators.
Tan et al. (2010)	<p><i>Type of research: empirical study on how two manufacturing companies approach services.</i></p> <p>The identified challenge to provide integrated solutions and services is:</p> <ul style="list-style-type: none"> - Feedback loop from service to product design: the organizational separation of product-oriented and service-oriented activities makes it challenging to share design relevant information, because of differences in business motivation, culture and language.

Table 2.2: Elements mentioned in the literature that affect addressing maintenance related aspects

2.3 Conclusion

This chapter gives an overview of the state of the art literature on the relevant maintenance aspects and on how they can be addressed successfully. A vast amount of literature is available on the aspects related to the product design, the product support and the contextual elements to be addressed. However, what is lacking is a deep understanding of how these aspects relate to the elements that need to be addressed for the development of maintenance services, and thus to develop competitive PSS/IPS² solutions. This is also reflected by the fact that the approaches to support the design of PSS/IPS² solutions are still under development. Also, little literature is available on how service elements, including the basic issues related to reliability, maintainability and support, are addressed by developers in practice. Insight on the developers' practices likely could help to understand how developers can be supported best to address the maintenance aspects successfully.

3 Introduction to the empirical study and relevance of addressing maintenance aspects

This chapter provides both an introduction to the empirical study that is performed in Dutch industry as part of Descriptive Study I (DS-I) and an answer to Research Question 1 (RQ1): *What is the relevance of addressing maintenance aspects in industrial equipment development projects?* This research question is meant to verify whether addressing the maintenance aspects is relevant for the companies involved in the empirical study.

The chapter starts by giving an introduction to the empirical study in Section 3.1. This is done by describing the steps that are taken to conduct it and the methods that are used. Then, Section 3.2 answers RQ1. Finally, Section 3.3 provides the conclusion to this chapter.

3.1 Introduction to the empirical study

The empirical study forms the main part of DS-I. The goal of DS-I is to provide a description of the current understanding in companies on how maintenance aspects can be successfully addressed, in order to determine which factor(s) should be addressed to support developers. The outcomes of DS-I are knowledge and insights on which are the relevant maintenance aspects, how these aspects can be successfully addressed and the factors that affect whether that is done successfully. As described in Section 1.6, DS-I consists of answering Research Questions 1, 2 and 3:

RQ1. What is the relevance of addressing maintenance aspects in industrial equipment development projects?

RQ2. What are the relevant maintenance aspects to be addressed in industrial equipment development projects?

RQ3. How can maintenance aspects be addressed in industrial equipment development projects and what factors affect whether this is successfully done?

The focus lies on answering RQ2 and RQ3, because these are the questions to be answered in order to learn what support could be useful for developers, while RQ1 is used to verify whether or not addressing the maintenance aspects is relevant for the companies involved in the empirical study. The focus within the research is on the construction of generic overviews to describe and explain the important maintenance aspects and how developers can address them. The study is not aimed at analyzing and improving the practices of the individual companies.

In the remainder of this section, I describe how the empirical study is set up and the steps that I have taken to come to the research results. Section 3.1.1 describes the overall design of the empirical study. Sections 3.2.2 and 3.2.3 describe the two main methods that are used to collect data: in-depths interviews and validation sessions. Also, these two sections describe the steps that are taken to analyze the retrieved data and to come to results.

3.1.1 Overall design of the empirical study

Figure 3.1 gives an overview of the empirical study. To answer the research questions, I have firstly held in-depth interviews with experts at three companies. Based on the analysis of the retrieved data and by projecting the findings on well-known frameworks from product development, I have constructed initial findings. Secondly, I have retrieved data via validation sessions. During these sessions, I have presented the initial findings to experts at the same companies and asked for their feedback. Based on their feedback, I have constructed the (final) findings. The findings consist of three overviews, which together answer RQ2 and RQ3: (1) an overview of the relevant maintenance aspects, (2) an overview of activities that developers perform to address maintenance aspects and (3) an overview of factors that affect whether maintenance aspects are successfully addressed. Below, I describe the companies and experts that I have selected for the empirical study.

Figure 3.1: Overview of the design of the empirical study

Description of involved companies

The research concerns the industrial equipment manufacturing industry. As discussed in Section 1.1, the equipment that companies in this industry develop, requires effective and efficient maintenance to achieve a good life cycle performance. The three companies are, in alphabetical order:

- ASML: a supplier of lithography systems for the semiconductor industry.
- Marel Stork Poultry Processing: a supplier of poultry processing systems.
- Vanderlande: a supplier of baggage handling systems, sorting systems for parcel and postal services and warehouse automation solutions.

I refer to the companies as Company 1, Company 2 and Company 3, which is not necessarily the alphabetical order in which the companies are listed above.

Besides the fact that all three companies develop industrial equipment, the companies have a number of other similarities. These similarities are:

- The companies market, develop and produce industrial equipment and they also develop and deliver services to their installed base. All companies deliver services that are categorized, in Figure 1.4, as basic installed base services and maintenance services. The extent to which professional services and operational services are offered, differs between the companies. The companies have to deal with a situation in which they provide a variety of services, different per customer, as discussed in Section 1.2 and illustrated in Figure 1.4.

- The equipment that the companies supply can be regarded as static, concentrated, specific technical systems (see Figure 1.1): it is used in used in production systems at fixed locations.
- The companies have a department and employees dedicated to the development and delivery of maintenance services.
- The companies have indicated that maintenance aspects play an increasingly important role in their development activities. Section 3.2 confirms that this is the case.

These similarities make it likely that similar results are found with respect to the relevant maintenance aspects and the way in which they are addressed. The similarities indicate that the experts at the three companies are dealing with similar aspects about which they need to make decisions. This means that the knowledge that is retrieved from the involved experts at the different companies complements each other. Involving experts from three companies thus enables getting a broader view than when only experts from one company are involved.

Description of involved experts

The interviews and feedback sessions are held with employees that are active in developing the equipment and/or the related maintenance services. I have involved two types of employees to which I refer with *equipment developers* and *maintenance service developers*, respectively. Equipment developers are employees that represent the design function of the companies. They are part of the research, development and/or design engineering departments and they are, for example, responsible for the mechanical design of the equipment. Maintenance service developers are employees that represent the service development function of the companies. They are part of departments that are responsible for the development and implementation of improvements with respects to the services that the companies deliver. They, for example, develop and improve maintenance schemes and implement new service solutions. They have regular contact with the customer and employees of the companies' service organizations, such as service engineers. Also, they are involved in new equipment development projects. Involving both type of employees is important, because both have relevant knowledge with respect to the research topic.

Tables 3.1 shows for each company the number of each type of employees that are interviewed. Tables 3.2 shows this for the employees who participated in the validation sessions. At company 1, employees to which I refer with *equipment/maintenance service developers* are involved instead of equipment developers. They are employees who represent the service development, but who are also part of the core development teams and work with the equipment developers on a daily basis.

Company	Type of employees	
Company 1	Equipment/maintenance service developers	1
	Maintenance service developers	2
Company 2	Equipment developers	1
	Maintenance service developers	1
Company 3	Equipment developers	1
	Maintenance service developers	1

Table 3.1: Employees interviewed at the involved companies

Company	Type of employees	
Company 1	Equipment/maintenance service developers	2
	Maintenance service developers	3
Company 2	Equipment developers	1
	Maintenance service developers	2
Company 3	Equipment developers	2
	Maintenance service developers	3

Table 3.2: Participants of the feedback sessions at the involved companies

3.1.2 Data collection method I: in-depth interviews

The use of in-depth interviews is the first method that I have used to collect data (see Figure 3.1). In-depth interviews make it possible to explore the tacit knowledge of the experts in the companies. Figure 3.2 shows the steps that are taken to gather and analyze the data. The rectangles are the activities that are performed and the rounded boxes show the outcomes of the activities. The steps are clustered in three main categories: data gathering, data analyzing - step 1 and data analyzing - step 2. Below, I describe these steps according to these clusters.

Data gathering

To gather data via in-depth interviews, I have used the interview guide approach (see Patton, 2002, pp. 342-344). According to this approach, a list of questions and issues to be raised, is made prior to the interviews. Using the interview guide approach ensures that the same topics are covered in the different interviews. Besides that, it gives the freedom to structure each interview differently. That makes it possible to explore a particular topic in more or less depth, depending on the area of expertise of the interviewee. For example, during interviews with equipment developers relatively more time can be spent on technical issues. During interviews with maintenance service developers, more attention can be given to discuss the maintenance and services processes.

The interview guide that I have used, is supplied in Appendix 2. It contains four parts.

1. The first part consists of background questions about the interviewee, the company, its business activities and the equipment that the company provides. These questions are meant to get a basic understanding for the remainder of the interviews.
2. The second part that contains questions about the maintenance on the equipment. These questions are meant to understand the role that maintenance has for good performance of the equipment during its use life cycle phases. These questions are meant to get insights into the relevance of addressing maintenance aspects, which is the topic of RQ1.
3. The third part contains questions about how the design of the equipment affects the maintenance activities. These questions are meant to retrieve data about the relevant maintenance aspects, which is the topic of RQ2.
4. The fourth part that contains questions about the development process of the company and how maintenance aspects are addressed during this process. These questions are meant to retrieve data about the way how maintenance aspects are addressed during equipment development processes, which is the topic of RQ3.

Table 3.1 shows the employees that I have interviewed. Each of them is interviewed separately. The interviews lasted approximately one and a half hour. All interviews were recorded, so that a

thorough analysis could be performed afterwards. To illustrate the depth of the interview and the way in which different topics are discussed, I have added examples of parts of the conversation in Appendix 3.

Data analyzing – step 1

To be able to analyze the data in detail, I have transcribed the interview recordings verbatim by using qualitative data analysis software (ATLAS.ti, version 7)¹. Use of the software enabled relating particular parts in the transcriptions to the audio file. In later stages of the data analysis process, the software is used to play back particular parts of the interviews in order to avoid misinterpretations of the data. The first step of analyzing the data is the use of mind maps to organize all the retrieved data. During the interviews, a wealth of relevant data was received of which the content went beyond the topics of the interview questions. I have used the mind maps to find a way to categorize the relevant data and to get more insight into the research topic. For each interview a mind map is made. In these mind maps all the retrieved data is categorized into five topics, namely data related to (1) the business activities of the companies, (2) the description of the equipment (3) maintenance on the equipment (4) relevant maintenance aspects and (5) the development process. Also, the interrelations between data of different topics are marked. Appendix 4 shows an illustration of the structure of such a mind map.

Data analyzing – step 2

The preparation of the mind maps and the analysis of the data within the mind maps have given a better understanding of the research topic. As already indicated in the description of the previous step, the relevant data that was retrieved during the interviews went beyond the topics of the questions that are listed in the interview guide. Based on the insights that were retrieved during the preparation of the mind maps, I have constructed a new set of questions that should be answered to construct complete answers to the research questions. I refer to these questions as information retrieval questions (see Figure 3.2). These questions are thus not used in the interviews. The set of information retrieval questions is supplied in Appendix 5. I have used this set of questions to distill the useful information from the mind maps and the transcriptions. Also this is done for each interview separately. The results are overviews in which useful information from the interviews is categorized per information retrieval question. These overviews are used as starting point for the construction of the initial findings. They are constructed by taking an overarching look at the useful information from the interviewed experts of the three companies. In this step the useful information from the different interviews is combined and used to construct the initial findings, which are supplied in Appendix 6. The initial findings are initial versions of the model of relevant maintenance aspects (see Section 4.1), the overview of activities that developers perform to address maintenance aspects (see Section 5.2.2) and the overview of factors that affect whether or not addressing maintenance aspects is done successfully (see Section 5.3.2). I describe the reasoning behind the construction of the overviews in the sections that present the findings.

¹ See www.atlasti.com

Figure 3.2: Steps followed for gathering and analyzing data via in-depth interviews

Figure 3.3: Steps followed for gathering and analyzing data via validation sessions

3.1.3 Data collection method 2: validation sessions

Holding validation sessions is the second method of collecting data in the empirical study. I have used these sessions to investigate if the initial findings give a good representation of the relevant maintenance aspects of the involved companies and of the way that developers address them. Furthermore, it gave the possibility to retrieve feedback from other persons than the ones that were originally interviewed, corroborating evidence on the validity of the results. Figure 3.3 shows the steps that are taken to gather and analyze the data. The steps are clustered in two main categories: data gathering and data analyzing. Below, I describe the steps according to these clusters.

Data gathering

The preparation of the validation sessions is done through (1) making a presentation on the main results of the research, (2) designing a feedback form and (3) preparing a document that includes the initial findings and, for each company separately, a description of the information provided per company. The feedback form is supplied in Appendix 7. It contains questions on the completeness and correctness of the initial findings, the currently relevant topics in industry and the usefulness of the research results. At each company, a presentation is held to a group of invited employees. Table 3.2 gives an overview of their roles. During and after the presentations, the research results were discussed. I have made notes on the issues that were raised during the discussions. Afterwards, a number of the participants has filled in and returned the feedback forms. In total, six feedback forms were returned from seven persons (two persons have together filled in one form). Appendix 8 shows the feedback that was provided.

Data analyzing

The data retrieved via the validation sessions consists of the notes made and the feedback forms retrieved from the companies. Analysis of this data is done through studying the issues that were raised and reasoning on how the feedback could be used to improve the initial findings. Both the issues raised during the sessions and the feedback from the feedback forms confirmed that the model and overviews give a correct and almost complete picture of the relevant maintenance aspects, the development activities during which they are addressed and the factors that affect whether or not addressing the maintenance aspects is done successfully. A number of suggestions was given on aspects, activities or factors to be added. These were incorporated in the final results. The exact additions can be found in Appendix 9. The reasoning behind making the additions are described in Sections 4.1, 5.2 and 5.3.

3.2 Relevance of addressing maintenance aspects

This section describes the findings related to RQ1: *What is the relevance of addressing maintenance aspects in industrial equipment development projects?* As explained in Section 1.6, this research question is meant to verify whether addressing the maintenance aspects is relevant for the companies that were involved in the study. During the interviews, the interviewees have indirectly mentioned a number of reasons that explain why it is relevant for their companies to address the maintenance aspects. Section 3.2.1 discusses these reasons. The interviewees have also given a number of reasons that explain why they consider it to be important to *improve on* addressing maintenance aspects. These are discussed in Section 3.2.2.

3.2.1 Relevance of addressing maintenance aspects for companies' business

During the interviews and validation sessions, it became clear that it is certainly relevant for developers at the involved companies to address maintenance aspects. In this section, I describe four lines of reasoning that show why it is considered to be relevant. These four lines of reasoning

are based on remarks that interviewees have made during the interviews. Each line of reasoning is accompanied by an explanation and by examples of related relevant maintenance aspects. Also, I provide quotes from the interviews that illustrate that the reasons are mentioned by the interviewees. The overarching findings at the end of this section describe my interpretation of what is important to consider when the relevance of addressing maintenance aspects is discussed. I also relate the lines of reasoning to Sections 1.1 and 1.2, in which is also discussed why addressing maintenance aspects is important during the development of industrial equipment.

1. It is essential that maintenance can be performed effectively and efficiently to meet the equipment's technical performance and productivity specifications.

Customers demand equipment that is capable to produce high quality goods and with which they can achieve high productivity rates. Availability and reliability are important performance indicators with respect to the productivity. High performance on these indicators can only be achieved, when during the development of the equipment, the effect of design decisions on the future maintenance is considered. Many of the decisions made on the equipment design affect what maintenance is required, when maintenance is required, how well maintenance can be predicted and how much time maintenance activities take. Therefore, they determine to a large extent which maintenance strategy can be followed and which performances can be achieved. Three examples are:

- Wear behavior of components affects when maintenance is required and if maintenance on different components can be clustered.
- The architecture of the equipment determines whether a maintenance action comprises the exchange of a module or of a part, affecting the time that is required for the maintenance action.
- The installment of sensors and performance measuring features enables the application of predictive maintenance strategies, affecting how well maintenance can be predicted.

[Interview at Company 1] “Productivity is important for our customers, because it determines how many products can be produced per day. [...] Important parameters with respect to the productivity are availability, reliability and maintainability.”

[Interview at Company 2] “The big drive to focus on maintenance aspects is that less and less time is available for maintenance. Therefore, the maintenance activities need to be performed quicker and smarter.”

2. Features on the equipment that enable quick and easy maintenance enhance the marketability of the equipment.

Features on the equipment that make maintenance quick and easy to perform are attractive for potential customers. Such features make maintenance less time consuming and less costly. The fact that the equipment becomes more complex and technologically advanced, makes them even more important. As the systems become more complex, generally also the maintenance activities become more complex, which requires advanced knowledge and skills of service engineers. Within this context, special features that help to solve breakdowns quickly are relevant. Service engineers must be able to quickly perform diagnosis, repair or replacement, and recover actions on the equipment, preferably without any additional support. Examples of features making maintenance quick and easy to perform and/or less costly, are:

- Diagnostic tools that help to find the root cause of a fault and explain the required maintenance action, either integrated in the operating systems of the equipment or supplied separately.
- Built-in automated maintenance functionalities that take over maintenance activities of a service engineer.
- Initialization features and built-in sensors that automatically detect faults and indicate that a maintenance action is required, in order to avoid further consequential damage.
- Easily exchangeable and affordably priced modules or components which are prone to regular failure but are not predictable.

[Interview at Company 3] “For a particular part of our system we have an old and a new system. For the new system, it takes only thirty seconds to remove a part, while it took 15 minutes for the old system. This is an example of something that we did to enhance the maintainability of the equipment. It improves the marketability of the equipment.”

3. Customers take life cycle performance criteria into account when they acquire new equipment.

Customers pay attention to the costs that they need to make over the whole equipment’s life cycle and not base their choice for a particular machine only on the initial investment. For the equipment manufacturers, this means that the equipment’s price, economic life time and maintenance and operation costs must be balanced with each other. Achieving a good balance requires that developers must address the effect of decisions on the equipment design on these performance criteria. This adds extra complexity to the issues described in the first and second lines of reasoning, as also the effect of design decisions on the price, life time, operation and maintenance cost must be taken into account. It comprises considerations on, for example:

- The effect of the choice for particular components, with a certain wear behavior and reliability level, on the life time of the component in combination with the effect of the price of the components on the equipment price and costs to be made for spare parts.
- The effect of the equipment’s architecture, its structure and modularity, on the time that maintenance activities take in combination with the costs of holding particular components or modules on stock.
- The effect of a choice for using particular technologies and components in combination with the effect on the costs to be made for personnel and tools to perform maintenance.

[Interview at Company 2] “You want to keep the cost of ownership as low as possible. [...] For the calculation of the cost of ownership, you look at the price of parts, estimate the costs of assembly, and they must be in balance with the price of the equipment.”

4. Equipment manufacturers get a more important role in the performance of maintenance.

In line with the discussion of the changing business activities of equipment manufacturers in Section 1.2, the involved companies also increasingly provide maintenance related services. The extent to which this is the case differs between the companies. In general, it can be said that delivering maintenance services and the responsibility for the performance levels of the equipment is becoming more important for all three of the companies. This development is driven by the customers who increasingly ask the equipment manufacturers to deliver maintenance services or even to take over the management of the maintenance and/or operation function. A reason for this is that the customers expect that the equipment manufacturer is an expert in maintaining the complex equipment and could help to achieve high performance levels.

The equipment manufacturers respond to that by developing and delivering such maintenance services. For them it is important to be able to achieve the performance levels that the customers expect. That means that the equipment manufacturers must be able to deliver maintenance timely and quickly. Examples of aspects that then become particularly relevant to address, are:

- Functionalities to gather data on wear and failure behavior and performance of the equipment in combination with an organization that analyses the retrieved data.
- Functionalities on the machines and external systems that enable remote monitoring of the equipment.
- Support systems with 'second-line' help desk engineers that can provide support to service engineers on distance, when necessary.

[Interview at Company 1] "After the warranty period, the customer has the choice whether he will perform the maintenance himself or performs it partly himself. There are all kinds of service contracts that are offered. [...] The customer can also get a contract in which a certain uptime is guaranteed."

[Interview at Company 2] "We get more and more questions from the customer to take over the maintenance activities."

[Interview at Company 3] "The customers ask us to perform the maintenance because they want to have a functioning system for the best price. If there are any problems, they want to have them solved by us."

Overarching findings

The four lines of reasoning show that the importance of addressing maintenance aspects is driven both by the need for providing competitive equipment offerings, so that customers can achieve a good life cycle performance, and by the need for offering competitive services. They also show a variety of maintenance aspects that are relevant to address in order to develop competitive equipment and maintenance services. What a competitive offering means exactly, depends on the individual customer's needs and the equipment or other solutions that competitors provide. Customers have different goals and the role that the equipment manufacturer has in the performance of the maintenance activities can be different as well (as also illustrated in Figure 1.4). That affects which aspects are the most important to focus on in a development project.

The reasons why it is important to address maintenance aspects are also discussed in Sections 1.1 and 1.2. Section 1.1 describes that addressing maintenance aspects is of key importance to obtain equipment with which a good performance can be achieved during the use and support life cycle phases. Lines of reasoning 1, 2 and 3 are related to this. Section 1.2 discusses that maintenance aspects become more important to address due to the changing business activities of equipment manufacturers, in which their role in performing maintenance becomes larger. Line of reasoning 4 shows that this is also relevant for the involved companies.

3.2.2 Relevance of improving on addressing maintenance aspects

As described in Section 1.3, successful product development requires high performance on dimensions related to both the products being developed and the related development process. The lines of reasoning described in the previous section, Section 3.2.1, concern the aspects that make the product and services of the company perform well. These are related to the product dimension. The empirical study also provides insights into the relevance of improving on process related dimensions. The objective of development projects is not only the development of the best possible product or service, but also to do that within the available development time and

budget. Below, I describe three potential areas of improvement that the interviewees have mentioned and provide quotes from the in-depth interviews that show that the areas of improvement are mentioned by the interviewees. At the end of this section, overarching findings are discussed. These overarching findings describe my interpretation of what is important to consider when discussing the importance of improving on addressing the maintenance aspects.

1. There is potential to improve on addressing maintenance aspects during the early stages of a development project.

The main potential of improving in addressing maintenance aspects concerns the improvement of addressing them in the early stages of a development project. Elementary design decisions, which are made in the early stages, can have a considerable impact on the future maintenance. If in these early stages the effect of decisions on maintenance is not considered, it might be possible that the specifications on the equipment performance are not met and rework is needed to solve it. However, later in the development process only limited possibilities exist to change the design. Then, it is also time-consuming to make such changes. If change are necessary, it can have the undesired consequence that the moment when the new equipment is launched to the market needs to be postponed.

[Interview at Company 1] “We could still make improvements with respect to addressing the maintenance aspects earlier in the development process. [...] If later on during the development process something needs to be corrected, it consumes a lot of time and it will be on the expense of other things that need to be done. Then it also costs a lot of money.”

[Interview at Company 2] “You cannot make calculations and simulations for everything, but calculations and simulations can really help to make a better design choice. It can provide, at an as early as possible moment, feeling about the effect of design choice on the wear behavior.”

2. Applying a more systematic approach in addressing maintenance aspects could prevent that maintenance aspects are overlooked.

Traditionally, many of the design decisions that are related to maintenance are based on gut feeling. The knowledge and experience of individual developers or of a development team determines which aspects are addressed and affects which design decisions are made. Using systematic approaches to address maintenance, for example in evaluating an equipment design on maintenance aspects, could help to decrease the dependence on the individual developer's knowledge, skills and experience. It helps to identify which aspects must be addressed in early stages of a development project, avoiding rework later in the project whenever developers overlook the effects of equipment design on maintenance.

[Interview at Company 3] “We could improve on discussing the relevant aspects by looking systematically at the requirements that are developed at the start of the development project.”

3. Making better use of the already available knowledge in the companies could help to make better design decisions regarding maintenance aspects.

Developers consider the availability of data and knowledge of key importance for making good design decisions with respect to the maintenance aspects. Within a company, a variety of resources is available that could provide such data and knowledge. For example, the service department can provide data and knowledge on the wear and failure behavior of the equipment in the field. Marketing and sales departments can provide data and knowledge on the costs allowed to be made for maintenance. However, such resources are not always used to its full potential during the development process. Improving on that can help to make design decisions that lead to competitive equipment and service offerings.

[Interview at Company 1] “The quality and quantity of the information that we get could be improved. [...] There are several opportunities to improve the feedback from the field.”

[Interview at Company 2] “It can be difficult and time-consuming to find the right information. It is useful when people who have experience in the field and know the equipment that I develop, could provide me with targeted information.”

[Interview at Company 3] “A possible improvement that has the most added-value for me is the improvement of the reliability of the information that we get about the system. For example, it would be useful to get reliable information about the performance and the failure behavior of the systems.”

Overarching findings

These three areas of improvement indicate how companies could improve their development with respect to maintenance aspects. However, the importance of improving on maintenance aspects also depends on their relative importance with respect to other aspects. If customers desire particular equipment because it has specific functionalities, then it may be less a problem if maintenance aspects do not get the full attention.

3.3 Conclusion

The goal of Descriptive Study I is to provide a description of the current understanding in companies on how maintenance aspects can be successfully addressed in order to determine which factor(s) should be addressed to support developers. The empirical study gives an overview on why it is relevant for equipment manufacturers to address maintenance aspects, what the relevant maintenance aspects are, how they can be addressed and what factors affect whether addressing them is successfully done. The findings related to Research Question 1 confirm the relevance of addressing maintenance aspects at the involved companies. Addressing maintenance aspects is essential (1) to meet the technical performance and productivity specifications of the equipment, (2) to enhance the marketability of the equipment, (3) to fulfill the customer's demands regarding the equipment's life cycle performance and (4) to ensure that the equipment manufacturers can deliver competitive maintenance services. The empirical study also indicates that improving on addressing maintenance aspects is relevant in order to make the development process more effective and efficient. Potential areas of improvement are (1) addressing maintenance aspects early in the development process, (2) using systematic approaches and (3) making better use of the knowledge available in the companies.

4 Relevant maintenance aspects to be addressed

This chapter provides the findings related to Research Question 2 (RQ2): *What are the relevant maintenance aspects to be addressed in industrial equipment development projects?* To answer the question, I have developed the model of relevant maintenance aspects that is presented in Figure 4.1 and described in Section 4.1. The model is the core research result with respect to RQ2. It is constructed by projecting the information that was provided via the empirical study (see Section 3.1) on a framework from the literature in product development. This framework is used to structure the information according to the way it is used to make decisions in product development projects. The developed model of relevant maintenance aspects follows this structure and contains an overview of the aspects that developers can address to enhance the maintenance performance of the equipment. During the development of the model, the level of aggregation at which the aspects are described is explicitly considered. This is necessary in order to provide both a complete and a usable overview. The aspects are described at such a level of aggregation that they are specific enough to indicate concrete attributes that developers can address, while not being too detailed to describe very specific attributes of a design that are relevant for few type of systems only. Sections 4.2 and 4.3 provide context to the relevance of addressing the aspects in the model in two different ways. Section 4.2 illustrates the relevance of the aspects and their interrelatedness by showing a number of approaches that developers can use to address them. Section 4.3 discusses how the relevance of aspects differs over different development projects and how the relevance changes during development projects. Finally, Section 4.4 gives the conclusion.

4.1 Model of relevant maintenance aspects

The relevant maintenance aspects are all aspects that both affect the need for and the execution of maintenance during the life time of the equipment and that developers can address during a development project. The model in Figure 4.1 gives an overview of the aspects and organizes them in categories. As described in Section 3.1.2, an initial version of this model is developed based on the data that is retrieved via the in-depth interviews. The initial version is shown for completeness in Appendix 6 and it is supplied to the employees that participated in the validations sessions, which is described in Section 3.1.3. Based on the retrieved feedback, a number of additions are made to the model. These are summarized in Appendix 9. The construction of the model is discussed in more detail in Section 4.1.1. Section 4.1.2 provides a description of the categories within the model. Section 4.1.3 provides a reflection on the literature in order to explain how the aspects from the literature are included in the model and to explain what the added value of the model is.

4.1.1 Construction of the model

The goal of constructing the model is to provide an overview of relevant maintenance aspects in such a way that it can be used for decision making in development projects. The process of constructing the model can be divided into three steps. These steps are discussed in the remainder of this section.

Figure 4.1: Model of the relevant maintenance aspects

<p>Equipment design / maintenance service design aspects</p> <p>Maintenance service design perspective</p>	<p>System and component wear and failure behavior:</p> <ul style="list-style-type: none"> - Wear behavior: mechanical and electronic components - System robustness <p>System complexity: control equipment / software components</p> <ul style="list-style-type: none"> - Interdependencies between components and sub-systems - Diagnostic and testing properties <p>Safety properties</p> <p>Remanufacturability properties</p> <p>Used technologies</p> <ul style="list-style-type: none"> - Built-in automated maintenance functionalities - Monitoring and data gathering functionalities 	<p>System complexity / Easiness to diagnose</p> <ul style="list-style-type: none"> o Maintenance support services and diagnostic tools o Service environment / Service engineer knowledge and skills 	<p>Maintenance resources customer and maintenance provider</p> <ul style="list-style-type: none"> - Service engineer knowledge and skills - Spare parts inventory management strategy - Maintenance tools inventory <p>Differences in performing maintenance</p> <ul style="list-style-type: none"> - Whether or not maintenance actions are performed - Proper diagnostics versus swapping parts <p>Life cycle policy suppliers: availability components</p> <p>Escalations by customers: additional preventive maintenance actions without technical explanation</p>
<p>Equipment design / maintenance service design aspects</p> <p>Maintenance service design perspective</p>	<p>Maintenance service design aspects</p> <p>Maintenance deliverables</p> <ul style="list-style-type: none"> - Maintenance scheme: items, actions and planning - Customized maintenance scheme: actions and planning - Maintenance manuals - Maintenance diagnostic tools - Initial spare parts list - Training service engineers / knowledge transfers - Safety procedures <p>Maintenance resources</p> <ul style="list-style-type: none"> - Service engineers - Maintenance tools - Spare parts inventory - Maintenance tools inventory - Remanufacturing organization <p>Maintenance process improvement</p> <ul style="list-style-type: none"> - Data gathering and analysis - Improvements maintenance scheme - Maintenance management tools - Spare parts inventory management strategy <p>Maintenance support services</p> <ul style="list-style-type: none"> - Helpdesk support - Service engineer support: 1st, 2nd, 3rd line - Monitoring services 	<p>Equipment & maintenance service design aspects</p> <p>System and components wear and failure behaviour</p> <ul style="list-style-type: none"> o Maintenance scheme <p>Alignment components's wear and failure behaviour</p> <ul style="list-style-type: none"> o Maintenance scheme <p>System modularity</p> <ul style="list-style-type: none"> o Maintenance scheme / spare parts inventory management <p>System, sub-system and component redundancy</p> <ul style="list-style-type: none"> o Maintenance scheme / spare parts inventory management <p>System and component standardization</p> <ul style="list-style-type: none"> o spare parts inventory management <p>System complexity / Easiness to diagnose</p> <ul style="list-style-type: none"> o Maintenance diagnostic tools / Maintenance support services <p>System built-in automated maintenance functionalities</p> <ul style="list-style-type: none"> o Required service engineers / Maintenance scheme <p>System monitoring and data gathering functionalities</p> <ul style="list-style-type: none"> o Maintenance scheme / Maintenance process improvement <p>Scenario specific wear behaviour</p> <ul style="list-style-type: none"> o Customization maintenance scheme / Maintenance process improvement <p>Remanufacturability properties</p> <ul style="list-style-type: none"> o Maintenance scheme / Remanufacturing organization 	<p>Maintenance resources customer and maintenance provider</p> <ul style="list-style-type: none"> - Service engineer knowledge and skills - Spare parts inventory management strategy - Maintenance tools inventory <p>Differences in performing maintenance</p> <ul style="list-style-type: none"> - Whether or not maintenance actions are performed - Proper diagnostics versus swapping parts <p>Life cycle policy suppliers: availability components</p> <p>Escalations by customers: additional preventive maintenance actions without technical explanation</p>

Step 1. Basic structure

The first step in the construction of the model is the selection of the basic structure. The basic structure is depicted in Figure 4.2. It originates from the frameworks that Jauregui Becker & Wits (2013) and Schotborgh et al. (2012) use to classify design information according to its role in the development process. The frameworks describe the information according to the way in which it is used for making design decisions. In those frameworks, there are three categories of aspects. For my setting, they are the following (they are discussed in more detail in Section 4.1.2). Firstly, *performance aspects*, representing the performance indicators of the maintenance that needs to be performed on the equipment. These aspects are used to set development goals and to evaluate the outcome of development activities. Secondly, *scenario aspects*, representing external factors that affect the performance aspects and that are outside the direct range of influence of the developers. Thirdly, *equipment design / maintenance service design aspects*, representing the aspects related to the embodiment of the object being designed, i.e., the aspects on which developers make decisions to influence the performance aspects. Developers need to anticipate on the scenario aspects when making decisions with respect to the equipment design / maintenance service design aspects.

Figure 4.2: Basic structure of the model of relevant maintenance aspects

Step 2. Selection of aspects and forming sub-categories

During the second step in the construction of the model the aspects are selected and the sub-categories of the category equipment design / maintenance service design aspects are formed. For this step, I have used the desired information from the penultimate step of the analysis of the data that was retrieved from the in-depth interviews (see Figure 3.2). During that step, the data retrieved from the interviews is structured according to the questions that are supplied in Appendix 5.

The relevant questions for the selection of the aspects in the model, are:

Question 3b: What design aspects of the equipment influence the need for and the performance of maintenance?

Question 3c: What aspects, other than the design aspects of the equipment, influence the need for and the performance of maintenance?

I have studied the information that answers these questions and formulated the aspects to be included in the different *categories* of the model. To illustrate how the information from the interviews provides information about the aspects to be included in the model, I provide two quotes from the in-depth interviews. For each of these quotes, I describe which aspects can be formulated from information that is provided by the quotes.

[Interview 7] “This particular part is often the cause of a failure, but the cause is not always the same. There are two things that are relevant. The amount of maintenance that customers perform differs across our customers, which also causes the failure behavior of the systems to be different.”

But also, we have different types of parts within our systems, of which the material slightly differs, which also causes the failure behavior to be different.

This quote provides the following relevant aspects in all three different categories:

- Performance aspect: the frequency that a component fails and thus a corrective maintenance action is required.
- Scenario aspect: the amount of maintenance that customers perform.
- Equipment design / maintenance service design aspect: the type of component that is selected and the related wear and failure behavior.

[Interview 5] “One of our sub-systems contains a bearing housing. We have many different types of this bearing housings. Now, we try to standardize and only to use a maximum of four different types. [...] The selected housing is easier to maintain, you need a particular tool. You could imagine that such a development makes it very attractive for the customer to work with exchange units. [...] You can tell the customer that he only needs a few different types of housing on stock for the complete installed base.”

This quote provides the following relevant aspects in all three different categories:

- Performance aspect: no performance aspect is directly mentioned, but via logical reasoning, you can define that the described development affects the maintenance costs and maintenance time.
- Scenario aspect: the spare parts inventory management strategy of the customer (if the customer is responsible for that).
- Equipment design / maintenance service design aspects: standardization of components, maintenance tools and the spare parts inventory management strategy (if the equipment provider is responsible for that).

As discussed in the introduction of this chapter, the aspects are described at such an aggregation level that they are specific enough to indicate concrete aspects that developers can address, but are not too detailed that they describe very specific attributes of a design that are relevant for few types of systems only. For example, within the quote from Interview 5 that is provided above, one of the aspects is formulated as *standardization of components* and not as *standardization of bearing housings*.

As discussed at the start of this section, within this second step, also the four *sub-categories* of the *category* equipment design / maintenance service design aspects are formed. These sub-categories are formed to enhance the usefulness of the model through ordering the aspects. The four sub-categories are constructed based on three insights that the information from the in-depth interviews provides.

Firstly, the information shows that both aspects related to the equipment and aspects related to the maintenance service design are important to address. Therefore, different sub-categories are created for *equipment design aspects* and *maintenance service design aspects*. In this context, the term maintenance service design is used for all aspects (within the category of equipment design / maintenance service design aspects) that are relevant to address and are not part of the equipment itself. The quote from Interview 5 shows an example of both an aspect related to the equipment design, namely *standardization of components*, and an aspect that is considered as part of the maintenance service design, namely *maintenance tools*. Secondly, the information shows the importance of considering the interrelations between the equipment design and the environment in which the system is operated and maintained. Therefore, the sub-category

scenario related equipment design aspects is made that represents these interrelations. The quote from Interview 7 that is provided above shows an example of such an interrelation. It shows that it is important to consider the wear and failure behavior of components in relation with the maintenance that is performed by the customer. Thirdly, the information shows that it is important to consider the interrelations between the equipment design and the elements that are developed as part of the maintenance service design. Therefore, the sub-category *equipment design & maintenance service design aspects* is formed, in which the relevant interrelations are listed. The quote from Interview 7 that is provided above shows an example: the interrelation between the standardization of components and the spare part management inventory strategy.

Step 3. Validation and improvement

Since I have used logical reasoning and own judgement in the first two steps of construction of the model, the third step in the construction of the model concerns the validation and improvement of the model. As discussed in Section 3.1.3, I have held validation sessions at the involved companies. Feedback on the model was retrieved both during the sessions and afterwards via the feedback forms. The answers to the questions at the feedback forms are supplied in Appendix 8. The retrieved feedback shows the following:

- The main categories of the model reflect the relevant topics at the companies. All provided answers at the feedback forms confirm this (see Appendix 8, Answers 1 to 5).
- The individual aspects in the initial model are correct and the model gives an almost complete overview (see Appendix 8, Answers 6 to 12).
- No suggestions are made to remove any of the individual aspects (see Appendix 8, Answers 6 to 12).
- Suggestions are made to add a number of individual aspects (see Appendix 8, Answers 7, 8, 11, 12, 17 and 21).

Based on the suggestions about aspects to add, the overview is improved. Also, a number of improvements is made to enhance the readability of the overview. For example, the terms used in the categories that represent the interrelations are made similar to the terms that are used in the other categories. Besides these relatively small changes, two larger modifications are made to enhance the usability of the overview:

- The item level aspects are specified at one more level of detail. The reason is that re-studying the data that was retrieved from the interviews gave the insight that developers use more specific performance indicators than were included in the initial model.
- The category system level performance aspects is added. The reason is that feedback retrieved via the feedback forms contains suggestions for adding the availability, the maintenance costs and the life cycle costs (see Appendix 8, Answers 11 and 12). As also discussed in the introduction of Chapter 2, these aspects are performance indicators that are related to the overall performance of the equipment and they represent the ultimate goal of addressing the maintenance aspects. The data retrieved via the in-depth interviews also contains other relevant aspects related to the overall performance of the equipment. In the final model, also these aspects are included.

4.1.2 Description of the categories of the model

This section provides a description of the categories within the model of relevant maintenance aspects.

Performance aspects

These are the performance indicators that represent the performance of maintenance. The performance aspects are categorized into two sub-categories: *system level performance aspects* and *item level performance aspects*. The sub-categories are defined as follows:

- *System level performance aspects* are the overall performance indicators of the equipment and maintenance service design being developed, which are affected by the maintenance activities that are performed. These are the performance indicators of interest for the user. Achieving a good level of performance on these indicators is the reason to address the effect of development decisions on maintenance. Two categories are distinguished, namely performance indicators related to (1) the technical performance criteria and (2) performance indicators related to life cycle performance criteria.
- *Item level performance aspects* are the performance indicators related to maintenance actions to be performed on an item, which can be a component or module, during the life time of the equipment. Two categories are distinguished, namely performance indicators related to (1) preventive maintenance actions and (2) corrective maintenance actions. The performance indicators are measures for the frequency of, the time required for and the cost that arise from the maintenance actions.

Scenario aspects

Scenario aspects represent the external factors that affect the performance levels on the relevant performance indicators, but are outside the direct range of influence of the developers. However, developers can anticipate them when making decisions on the equipment or maintenance service design. The interesting thing about the scenario aspects is that equipment manufacturing companies get more control over them when they provide services in which they take over the maintenance or operation of their customers. That is also the reason why a number of individual aspects in the model, for example the maintenance resources, are both listed under the headings of maintenance service design aspects and scenario aspects.

Equipment design / maintenance service design aspects

These represent the aspects related to the design of the equipment and to the maintenance service design on which developers can make decisions to influence the performance aspects. The relevant aspects are categorized into four sub-categories that are defined as follows:

- *Equipment design aspects*: characteristics and properties of the equipment itself. Examples are the structure of the system, the position of the items that require maintenance and the wear and failure behavior of components.
- *Maintenance service design aspects*: deliverables that are not part of the equipment itself, but are inextricably linked to the equipment being developed, and elements of the maintenance delivery services. Examples of the deliverables are maintenance manuals and diagnostics tools to support service engineers in diagnosing a fault. Examples of elements of the maintenance delivery services are the spare part management strategy and the helpdesk support.

- *Scenario related equipment design aspects*: equipment design and scenario aspects that affect each other and that together determine which levels of performance can be achieved on the maintenance related performance indicators. For example, the wear and failure behavior of components depends on the material properties of the component and on the environmental conditions, such as temperature and humidity, in which the equipment is used. Together they affect the frequency of corrective and preventive maintenance actions.
- *Equipment & maintenance service design aspects*: equipment design and maintenance service design aspects that affect each other and that together determine which levels of performance can be achieved on the maintenance related performance indicators. For example, the maintenance scheme follows from the wear and failure behavior of the equipment. The wear and failure behavior is influenced by the maintenance that is performed, which in itself is prescribed in the maintenance scheme. Together they affect the frequency of corrective and preventive maintenance actions.

The individual aspects in the model (Figure 4.1) are all aspects of which the interviewees and/or the participants of the validation sessions have indicated that they are relevant to address or that they at least need to be considered to address them. Thus, it does not mean that all aspects always need to be addressed when making a design decision. A reason for this can be that the functionality of the equipment is the main concern, and, for example, determines the need for a particular component. In such a case, the performance on maintenance related performance indicators can be of less concern or may not get any attention.

Item level performance aspects <i>Preventive maintenance Performance measures</i> Frequency - Time between preventive maintenance actions Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost			<i>Corrective maintenance performance measures</i> Frequency - Time between failures, failure rate Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost
Equipment design Aspects System structure and elements characteristics - Component selection System and component wear and failure behavior: - Wear behavior: mechanical and electronic components - System robustness	Scenario related equipment design aspects System and components wear and failure behaviour ◊ Environmental conditions / Operational conditions / Difference in performing maintenance System robustness ◊ Operational conditions	Scenario aspects Environmental conditions - Temperature, humidity, ... - Cleanliness, air contamination, ... Operational conditions - Use of the system - Load of the system - Cleaning regime of the system	
Maintenance service design aspects Maintenance deliverables - Maintenance scheme: items, actions and planning - Customized maintenance scheme: actions and planning Maintenance process improvement - Improvements maintenance scheme	Equipment & maintenance service design aspects System and components wear and failure behaviour ◊ Maintenance scheme Scenario specific wear behaviour ◊ Customization maintenance scheme / Maintenance process improvement		

Figure 4.3: Relevant maintenance aspects related to Approach I
“Minimizing the need for maintenance”

4.1.3 Reflection on the literature

Section 2.1 discusses the literature with respect to the relevant maintenance aspects. The section shows that different fields of literature discuss aspects that are important to consider when addressing maintenance in a development project. The aspects that are mentioned in the literature are related to the product, the product support and the elements of the maintenance delivery services. The model of relevant maintenance aspects that is presented in this chapter represents the different aspects in one overview and also explicitly represents the interrelations between the aspects. This is something that does not yet exist in the literature. The model also orders the aspects, based on the frameworks of Jauregui Becker & Wits (2013) and Schotborgh et al. (2012). These frameworks are used to classify design information according to the way in which it is used for making design decisions. This makes the model usable for developers in practice. Regarding the aspects within the model, especially the interrelations between the equipment and maintenance service design are something that is not yet explicitly presented in the literature. Considering these interrelations is particularly important when it concerns the development of offerings in which products and service elements are integrated.

4.2 Illustration of the relevance of the individual aspects

In this section, I illustrate the importance of the individual aspects in the model in Figure 4.1 by giving examples of approaches that developers use to affect the maintenance performance of the equipment being developed. When applying an approach, several of the aspects in the model are relevant to address. Figures 4.3 to 4.9 show the aspects that are important with respect to each of the approaches. The approaches together with the figures show that properly addressing maintenance aspects requires that developers do not consider the individual aspects separately. Instead, it is of key importance that developers consider the interrelations between the equipment design, the maintenance service design and the environment in which the equipment is operated and maintained. I have constructed the list of approaches based on own reasoning about the main categories of topics that are discussed during the in-depth interviews. However, the overview is not intended to be complete; it is used to illustrate the relevance of the individual aspects and their interrelations. Below, I describe each approach. For each approach, I provide quotes from the in-depth interviews that show the relevance of the approach and a number of the individual aspects.

Approach 1. Minimizing the need for maintenance (Figure 4.3)

The most basic approach used to improve the level of performance on the maintenance related performance indicators, is avoiding or minimizing the need for maintenance. Improving the life time of components and the use of technologies that do not need much servicing reduces the need for maintenance. Enhancing the robustness of the equipment reduces the risk of failures due to improperly use of the equipment and so affects the number of corrective maintenance actions to be performed. Also, during the use life cycle stage of the equipment, developers evaluate the maintenance schemes and adapt them to the needs for maintenance when the system is used in the customer environment. If possible, the frequency of preventive maintenance actions is decreased. Although it would be ideal, it is unrealistic to design equipment that does not need any maintenance during its life time. Therefore, developers also use the other six approaches that focus on minimization of maintenance time and costs.

Item level performance aspects		
<i>Preventive maintenance performance measures</i> Time - Time to support - Time to inspect - Time to maintain - Time to recover Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost	<i>Corrective maintenance performance measures</i> Time - Time to support - Time to diagnose - Time to repair/replace - Time to recover Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost	
Equipment design Aspects System structure and elements characteristics - Component selection - Component's size, dimensions, weight, ... - Structure characteristics, positioning of components, ... - Standardization: sub-systems, components, fasteners, ... Properties related to system reparability/ maintainability - Easiness to diagnose - Inspectability - Accessibility - Easiness to assemble/disassemble - Easiness for system recovery Safety properties	Scenario related equipment design aspects	Scenario aspects
Maintenance service design aspects Maintenance deliverables - Maintenance manuals - Safety procedures Maintenance resources - Maintenance tools		

Figure 4.4: Relevant maintenance aspects related to Approach 2
“Enhancing the equipment’s maintainability”

Item level performance aspects		
<i>Preventive maintenance Performance measures</i> Frequency - Time between preventive maintenance actions Plannability Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost		<i>Corrective maintenance performance measures</i> Frequency - Time between failures, failure rate Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost
Equipment design Aspects	Scenario related equipment design aspects	Scenario aspects
System structure and elements characteristics - Component selection System and component wear and failure behavior: - Wear behavior: mechanical and electronic components - System robustness	System and components wear and failure behaviour o Environmental conditions / Operational conditions / Difference in performing maintenance	Environmental conditions - Temperature, humidity, ... - Cleanliness, air contamination, ... Operational conditions - Use of the system - Load of the system - Cleaning regime of the system
Maintenance service design aspects	Equipment & maintenance service design aspects	
Maintenance deliverables - Maintenance scheme - Customized maintenance scheme	System and components wear and failure behaviour o Maintenance scheme Alignment components's wear and failure behaviour o Maintenance scheme	Differences in performing maintenance - Whether or not maintenance actions are performed

Figure 4.5: Relevant maintenance aspects related to Approach 3
“Aligning component life time with maintenance scheme”

[Interview 2] “My starting point for the development of a maintenance scheme is that I always try to minimize maintenance. However, the equipment needs to stay robust, keep functioning and deliver a good performance. So, you still need to perform the essential maintenance.”

Approach 2. Enhancing the maintainability of the equipment (Figure 4.4)

To reduce the impact that the maintenance activities have on the operation of the equipment, developers try to make the maintenance actions easy and quick to perform. A variety of the decisions that developers make on the equipment design influence the efforts that are required to perform a maintenance action. Examples of choices that developers can make, are: positioning components that regularly need maintenance at easily accessible locations; standardizing the use of fasteners so that service engineers only need a limited number of tools; and adjusting the components' size, weight and shape in such a way that a maintenance action can be performed by one person. Also, safety aspects are addressed to ensure that service engineers can perform the maintenance actions without a risk on injuries. From the perspective of the maintenance service design, developers can support service engineers in performing maintenance actions quickly through. They do this by providing clear and easily understandable maintenance manuals and safety procedures; and providing tools to make maintenance tasks easier to perform, such as devices to test machine functionalities and tools to position modules correctly in the main systems.

[Interview 2] “Ergonomics is also important. Heavy parts should not be positioned in such a way that they need to be lifted with outstretched arms. Then you need lifting tools and that is something you also do not want. Therefore, you need already to think about such things during the design phase. Also, aspects like the use of standard screws and the accessibility of parts is important. It should not be needed to remove other parts before you can reach something.”

[Interview 4] “I try to design the equipment in such a way that for the parts that need to be replaced during a revision only one type of wrench is required. Then you do not constantly need to change tools or to search for tools.”

Approach 3. Aligning components' life times with maintenance schemes (Figure 4.5)

The maintenance scheme gives an overview of the required preventive maintenance actions and the moment that they need to be performed. Developers try to schedule several actions together at one moment, so that the primary process is only disturbed at a limited number of moments and for a short time. Groups of actions are scheduled, for example, weekly, monthly and yearly or after a certain number of operating hours. A number of these maintenance actions require the preventive replacement of components. Replacement actions prevent failing of the equipment. To avoid discarding components that are not yet worn out and to avoid components failing before the scheduled moment of replacement, developers adjust the life times and the maintenance scheme to each other. For example, they try to improve particular components in such a way that they last until a following moment of maintenance or reschedule the replacement of components that last longer to an earlier moment. Customized maintenance schemes can be developed in order to adapt to wear and failure behaviour at particular customer sites.

[Interview 5] “For each periodic maintenance action, we take one part as trigger part and cluster the required maintenance of other parts around this trigger part, so that all parts will last until the next maintenance action. [...] Every part that is categorized into a particular periodic maintenance action, must have such a life span that it will last until the next planned periodic action.”

Item level performance aspects <i>Preventive maintenance performance measures</i> Time - Time to support - Time to diagnose - Time to repair/replace - Time to recover Direct maintenance costs - Cost for labour Indirect maintenance cost		<i>Corrective maintenance performance measures</i> Time - Time to support - Time to diagnose - Time to repair/replace - Time to recover Direct maintenance costs - Cost for labour Indirect maintenance cost
Equipment design Aspects System complexity: control equipment / software components - Interdependencies between components and sub-systems - Diagnostic and testing properties	Scenario related equipment design aspects System complexity / Easiness to diagnose ↻ Maintenance support services and diagnostic tools ↻ Service environment / Service engineer knowledge and skills	Scenario aspects
Maintenance service design aspects Maintenance deliverables - Maintenance manuals - Maintenance diagnostic tools - Initial spare parts list - Training service engineers / knowledge transfers Maintenance support services - Helpdesk support - Service engineer support	Equipment & maintenance service design aspects System complexity / Easiness to diagnose ↻ Maintenance diagnostic tools / Maintenance support services	

Figure 4.6: Relevant maintenance aspects related to Approach 4
“Reducing complexity of maintenance actions”

Item level performance aspects <i>Preventive maintenance performance measures</i> Time - Time to support - Time to inspect - Time to maintain - Time to recover Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost		<i>Corrective maintenance performance measures</i> Time - Time to support - Time to diagnose - Time to repair/replace - Time to recover Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost
Equipment design Aspects System structure and elements characteristics - Structure characteristics, positioning of components, ... - Modularity - Standardization: sub-systems, components, fasteners, ... Remanufacturability properties	Scenario related equipment design aspects	Scenario aspects Maintenance resources customer and maintenance provider - Spare parts inventory management
Maintenance service design aspects Maintenance deliverables - Maintenance scheme: items, actions and planning Maintenance resources - Service engineers	Equipment & maintenance service design aspects System modularity ↻ Maintenance scheme / spare parts inventory management System and component standardization ↻ spare parts inventory management Remanufacturability properties ↻ Maintenance scheme / Remanufacturing organization	

Figure 4.7: Relevant maintenance aspects related to Approach 5
“Designing modular equipment”

Approach 4. Reducing the complexity of maintenance actions (Figure 4.6)

Industrial equipment nowadays contains many mechanical, electronic and software components that are connected to and interact with each other. The many components and their interdependencies make problem solving a particularly complex task, as it can be difficult to find the cause of a fault. Although the systems are complex, it is desired that service engineers that have relatively less training, are able to solve a problem quickly under all possible circumstances. However, that does still mean that education and training of services engineers is required. In the development process, several aspects can be addressed to enable solving problems quickly. Developers can focus on developing control equipment that provides information on the faults that occur, such as the exact positing of a component that has failed and instructions on how to replace it. Possibly, the control equipment also provides information on the availability and location of the spare parts within the warehouse. Apart from the equipment design, developers can provide diagnostic tools, develop training for service engineers and support services to assist engineers in the field on distance.

[Interview 5] “With the equipment a good technological performance and also a good efficiency can be achieved. However, to achieve this, you also need good people with a good level of knowledge for the operation of the equipment.”

[Interview 7] “The control equipment should give the right information to the user and the service engineer.”

Approach 5. Designing modular equipment (Figure 4.7)

One way of solving a problem is repairing or replacing the component that causes the problems. Another way is to solve the problem by exchanging the complete module in which the problem arises. Implementing such a maintenance strategy requires that the equipment is built in such a way that modules are easily separable from the main system. Besides that, it requires smart thinking on which components form a module, as implementing such a strategy affects other processes of both the customer and of the equipment manufacturer. For example, it requires a different approach for the management of spare parts inventories. The user or maintenance provider needs to hold complete modules on stock instead of specific components. Also, it requires facilities and people to repair or remanufacture the modules removed from the equipment and an organization to handle that. Setting up and managing such facilities induces cost. These cost are traded-off against the indirect cost for maintenance that are avoided through the possibility to quickly get the equipment up and running again.

[Interview 5] “We try to use the modularity of our equipment, thus the possibility to isolate a sub-assembly from the main system, as a starting point to work with exchange units. This could be done for numerous modules. However, that sets requirements for the structure of the equipment. That is one of our points of attention nowadays in the early development stages.”

[Interview 6] “We have developed a new type for a particular product. We developed it in such a way that you can exchange a module instead of that you need to replace the part that is broken. You are up-and-running again within five minutes.”

Approach 6. Automation of maintenance actions (Figure 4.8)

Automation of maintenance can be done through developing equipment functionalities that take over maintenance actions from service engineers. Examples of actions that can be automated are daily servicing actions such as cleaning, lubricating and greasing, fault diagnosis (see also Approach 4), system recovery and checks to test if the equipment functions properly.

Item level performance aspects <i>Preventive maintenance performance measures</i> Plannability Time - Time to support - Time to inspect - Time to maintain - Time to recover Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost			<i>Corrective maintenance performance measures</i> Time - Time to support - Time to diagnose - Time to repair/replace - Time to recover Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost
Equipment design Aspects Used technologies - Built-in automated maintenance functionalities	Scenario related equipment design aspects	Scenario aspects Maintenance resources customer and maintenance provider - Service engineer knowledge and skills	
Maintenance service design aspects Maintenance deliverables - Maintenance scheme: items, actions and planning Maintenance resources - Service engineers	Equipment & maintenance service design aspects System built-in automated maintenance functionalities ◊ Required service engineers / Maintenance scheme		

Figure 4.8: Relevant maintenance aspects related to Approach 6

Item level performance aspects <i>Preventive maintenance performance measures</i> Frequency - Time between preventive maintenance actions Plannability Time - Time to support Direct maintenance cost - Cost for labour - Cost for spare parts Indirect maintenance cost			<i>Corrective maintenance performance measures</i> Predictability of failures Time - Time to support Direct maintenance costs - Cost for labour - Cost for spare parts Indirect maintenance cost
Equipment design Aspects System and component wear and failure behavior: - Wear behavior: mechanical and electronic components Used technologies - Monitoring and data gathering functionalities	Scenario related equipment design aspects System and components wear and failure behaviour ◊ Environmental conditions / Operational conditions / Difference in performing maintenance	Scenario aspects Maintenance resources customer and maintenance provider - Service engineer knowledge and skills	
Maintenance service design aspects Maintenance deliverables - Maintenance scheme: items, actions and planning - Customized maintenance scheme: actions and planning Maintenance process improvement - Data gathering and analysis - Improvements maintenance scheme - Maintenance management tools - Spare parts inventory management strategy	Equipment & maintenance service design aspects System and components wear and failure behaviour ◊ Maintenance scheme System monitoring and data gathering functionalities ◊ Maintenance scheme / Maintenance process improvement Scenario specific wear behaviour ◊ Customization maintenance scheme / Maintenance process improvement		

Figure 4.9: Relevant maintenance aspects related to Approach 7
“Implementing predictive maintenance strategies”

The latter has the goal to avoid, for example, quality problems and possible consequential damage when a malfunctioning system is operated. Automating such actions has the advantage that no service engineers are needed to perform them. That saves costs and eliminates the dependence on the availability of service engineers or on the skills that they need to perform the actions quickly and correctly.

[Interview 2] “I also look if it is possible to automate maintenance actions, for example the calibration of a motor. Our equipment has a functionality that can be used to schedule the automatic maintenance action, no operator is needed.”

Approach 7. Implementing predictive maintenance strategies (Figure 4.9)

Implementation of predictive maintenance strategies has both the purpose to predict failures so that maintenance actions can be timely prepared and to avoid discarding components earlier than necessary. It helps to minimize the required maintenance and to reduce the risk of failures. Prediction of failures can be done with different techniques. The basis is the monitoring of a particular parameter and the development of a model that accurately describes the wear and failure behaviour of a component in relation to the measured values. Three categories of parameters are used: time, performance and condition related parameters. Examples of parameters belong to each category are, respectively, calendar time, the number of start-ups of a system and components' wear. For implementing predictive maintenance strategies, developers first add monitoring and data gathering functionalities to the equipment and then analyses the retrieved data to build up knowledge on the wear and failure behaviour. Only if accurate models are available, it is possible to successfully apply predictive maintenance strategies. In addition to that, developers can add functionalities for remote monitoring of the equipment. It enables the maintenance provider, which can be the equipment manufacturer itself, to monitor and gather data on distance. That makes visits to the site for inspections unnecessary.

[Interview 2] “We perform preventive maintenance that is guided by preventive maintenance schemes, but you can also think about defining performance indicators that you would like to monitor.”

[Interview 7] “One of the goals to implement predictive maintenance strategies is that I do not need to send a service engineer to the customer site to inspect the system, but that I can monitor the status of the system on distance and that I am able to predict when a maintenance action will be required. To be able to do this, it is required that the wear behaviour is known. Therefore, you need to build up knowledge at a particular customer site and to add functionalities to the equipment that could tell something about the status of the system.”

4.3 Relevance of maintenance aspects during a development project

Section 4.1 presents the relevant maintenance aspects that developers can address to enhance the maintenance performance of industrial equipment. The current section discusses how the relevance of aspects differs over different development projects and how the relevance changes during development projects. The purpose of this section is to provide context to the relevance of these aspects. Not all aspects are always equally important and not all aspects can always be addressed. The relevance of addressing particular maintenance aspects can be related to (1) the goal of a development project and (2) the stage in which a development project is. Sections 4.3.1 and 4.3.2, respectively, discuss these two topics in more detail. The provided insights are based on the information that is provided via the in-depth interviews and on own reasoning about which insights this information gives.

4.3.1 Relevance of maintenance aspects and the goal of a development project

The goal of addressing the maintenance aspects is to enhance the maintenance performance of the equipment being developed. However, the desired performance itself and the extent to which it can be achieved are not the same in each development project. During the in-depth interviews, the experts have mentioned a number of things that are important to take into account. Below, I describe them grouped by three main points. For each point, I provide quotes from the in-depth interviews that are related to the discussed topics.

1. It is not possible to use a one-size-fits-all approach to define the desired performance.

The equipment manufacturers develop one product with which good levels of performance must be achieved in different situations. The desired performance and the scenario aspects are different for individual customers. This affects how much time and costs they allow to spend on maintenance. For example, customer can have different dimensions on which they compete. For quality competitors, extra expenditures for maintenance might be not a problem as it enhances the quality of the products. For cost competitors, high expenditures on maintenance may only be allowed when it results in less costs per product. Also, customers have arranged their primary process differently, which affects which maintenance strategy is the most suitable to apply. For example, one customer may only use the equipment for a limited number of hours of a day during which it is essential that the primary function can be performed. In such a situation there is sufficient time available during the other hours of the day to perform preventive maintenance. Another customer may need its equipment 24/7 and may desire that maintenance actions can be timely foreseen so that it can anticipate, for example, by rescheduling its primary processes.

[Interview 1] “There are different types of customers, each focusing on a particular end product market. The maintenance strategies that the customers apply are different.”

[Interview 7] “If you ask what the important key performance indicator is for a customer, you need to know which kind of customer it is. [...] And what is important for him? [...] We have a number of standard reports that we use for defining key performance indicators, but the customer can always say that other performance indicators are important for him and would like to use these to measure the system performance.”

2. The performance that can be achieved is maturity related.

For knowing which maintenance is required to achieve the desired equipment performance, one needs to go through a learning process. When introducing new systems, developers must learn how the systems function in a particular customer environment. They need to build up knowledge on the wear and failure behavior of the equipment and the parameters affecting it. This requires monitoring and analysis of the performance of the system and the maintenance actions that are performed. Also, the type of maintenance actions that needs to be performed, varies over the life time of the equipment. During the first part of the life time so-called infant mortalities occur. Often these are problems related to the control equipment and software elements which need to be solved. When the system is operated for a longer time, the wear and failure behavior of mechanical and electrical parts becomes clear. It may take a number of years before certain wear problems occur, which are undesired consequences of design choices that are made.

[Interview 5] “With respect to machines that are relatively new for us, we can get new insights with respect to the required maintenance. We need two to three years to be able to tell which maintenance scheme fits best to particular process circumstances.”

[Interview 3] “What you see is that you, for new machines, often have to deal with software issues that cause the systems to fail. We test the systems extensively before they are installed in

the field, but the conditions are never exactly the same as at a customer site. The customer uses the system in its own way. These are the problems you encounter first. Later on, you get to deal with things that break. [...] At the start, it merely are problems related to software, later on they are more related to hardware.”

3. The available development time and budget affects the extent to which developers can address the maintenance aspects.

The available development time and budget depends on strategic choices that companies make. The available time is, among other things, affected by the pressure that companies have to launch new products to the market (this is also discussed in Section 5.3.2). Within the available time, developers need to develop the most competitive product. Maintenance aspects are not the only aspects to be addressed. Developers need to determine how important they are with respect to all other aspects and which of the maintenance aspects are the most important to focus on.

[Interview 3] “The time-to-market is important. You could not wait until the product is perfect to bring it to the market, because then you will be the last one.”

4.3.2 Relevance maintenance aspects and the development process stages

Maintenance aspects are relevant throughout the whole development process. How maintenance aspects are addressed during the development process is discussed in Chapter 5, to which I refer a number of times in the current section. In the current section, I discuss how the relevance of aspects changes during the development process. As discussed in more detail in Section 5.1, the development process can be described by four stages:

- The feasibility stage during which developers generate and refine ideas for new products.
- The design / prototype stage during which developers transfer the ideas from the feasibility stage into a concrete design of the equipment.
- The detailing / pilot run during which developers finalize the design and install a first version of the equipment at a pilot site.
- The improvement / upgrading stage during which developers make improvements and develop upgrades for the equipment when it has already been put on the market and it is in use at various customer sites.

In order to describe how the relevance of aspects changes during the development process, I refer to Figure 4.10. This figure depicts when during the four stages of the development process the categories of relevant maintenance aspects (see Figure 4.1 for the categories and the related aspects) are relevant to address. The figure is constructed based on logical reasoning, starting from the insights that the in-depth interviews give with respect to both RQ2 and RQ3. Below, I discuss Figure 4.10. For each of the main categories in the model of relevant maintenance aspects, *performance aspects*, *equipment design / maintenance service design aspects* and *scenario aspects*, I explain when the related aspects are relevant to address and the reason behind it.

Figure 4.10: Illustration of the timing of addressing maintenance aspects in development projects

Performance aspects

The performance aspects are important throughout the whole development process. As discussed in Section 5.3.2, the *Factor 5. Quality of definition and use of performance indicators and requirements* is one of the factors that affect whether maintenance aspects are successfully addressed. Developers should define the important performance indicators and the desired levels of performance to be achieved. During the development process they represent the objective of the development project. Developers should use them to evaluate the outcomes of the development activities, which are the equipment and maintenance service design.

Equipment design / maintenance service design aspects

Developers should address all the aspects that are related to the equipment design from the start of the design/prototype development stage, i.e. from the moment that decisions on the equipment design are made. This is discussed in Section 5.3.2 under *Factor 7. Timing of addressing maintenance aspects*. Aspects that are related to the equipment design also include the interrelations that are listed as the equipment design & maintenance service design aspects. These represent the maintenance strategy. To enable the adoption of a particular maintenance strategy, developers are required to proactively think about which characteristics the equipment design must have to apply that strategy. Decisions concerning these aspects can only be made when properly looking at them from both the perspective of the equipment design and the maintenance service design. In the later stages of the development process, developers can focus on the maintenance service design aspects to further improve on the equipment's performance.

Scenario aspects

Developers should address the scenario aspects when making decisions on both the equipment design and the maintenance service design. The scenario aspects affect which levels of performance can be achieved in practice. Making good decisions on the equipment and maintenance service design can only be done through considering the elements of the environment in which the equipment is operated and maintained. As discussed in Section 5.3.2 under *Factor 1. Knowledge on maintenance aspects*, having knowledge on the interrelations between the equipment design and the environment in which the equipment is operated and maintained, is considered to be essential in order to address the maintenance aspects successfully.

4.4 Conclusion

Similar to the literature that is described in Section 2.1, this chapter shows that a variety of maintenance aspects are relevant to address during industrial equipment development projects. This chapter presents a model that gives an overview of the relevant aspects and that orders the aspects in a logical way: according to the way in which developers use them to make design decisions. Three main categories of aspects are distinguished. Firstly, the *performance aspects*, representing the maintenance related performance indicators that developers should define and use to evaluate the outcome of the development activities. Secondly, the *scenario aspects*, representing the external factors that affect the performance levels that can be achieved. They are outside the direct range of influence of developers, but developers need to anticipate them when making design decisions. Thirdly, the *equipment design / maintenance service design aspects*, representing the characteristics and properties of the equipment design, the maintenance deliverables and the elements of the maintenance delivery services, i.e. the outcomes of the development activities. Developers should make decisions on these aspects by considering their interrelations and the interrelations with the environment in which the equipment is operated and maintained.

Seven approaches that developers use to enhance maintenance performance demonstrate the relevance of the individual aspects. These approaches are: (1) minimizing the need for maintenance, (2) enhancing the maintainability of the equipment, (3) aligning components' life times with maintenance schemes, (4) reducing the complexity of maintenance actions, (5) designing modular equipment, (6) automation of maintenance actions, and (7) implementing predictive maintenance strategies. The approaches show that properly addressing the maintenance aspects requires that developers consider the interrelations between equipment design, maintenance service design and the environment in which the system is operated and maintained.

Finally, it is important to consider that not all aspects should or can always be addressed. The relevance of addressing particular maintenance aspects is related to (1) the goal of a development project and (2) the stage in which a development project is.

5 How maintenance aspects can be addressed

This chapter provides the findings related to Research Question 3 (RQ3): *How can maintenance aspects be addressed in industrial equipment development and what factors affect whether this is successfully done?* To answer the question, I have constructed (1) an overview of the development activities that developers perform to address maintenance aspects and (2) an overview of the factors that affect whether addressing maintenance aspects is done successfully, including extensive descriptions of all activities and factors. These two overviews are the core results with respect to RQ3 and are presented in Sections 5.2 and 5.3, respectively. They are constructed based on the information that was provided via the in-depth interviews and validation sessions. The in-depth interviews and validation sessions are described in Sections 3.1.2 and 3.1.3, respectively. Section 5.1 provides a general description of the role of maintenance aspects in different development process stages and the kind of activities that developers perform in each stage. It serves as introduction to Sections 5.2 and 5.3. Section 5.4 discusses the lessons learned regarding how maintenance aspects can be addressed successfully. Finally, Section 5.5 gives the conclusion.

5.1 The role of maintenance aspects in different development process stages

As discussed in Section 1.3, a development processes consists of a number of successive stages during which numerous iterations of development activities take place. In line with the literature (Blanchard & Fabrycky, 2014, which I have discussed in Section 2.2.1), the information from the in-depth interviews shows that maintenance aspects should be addressed in different development activities throughout the whole development process. The interviewed experts address maintenance aspects both explicitly and implicitly during many of the development activities that they perform, as they consider addressing maintenance aspects to be intricately linked with the overall development objectives that they need to fulfill. A comment made by an interviewee illustrates this:

[Interview 6] “Everything that you do during development is for service. If you do not need to take into account that, for example, a particular component needs to be replaced on a certain moment, it would be much easier to make development steps. You would be finished really quickly.”

In order to structure the description of how maintenance aspects are addressed throughout the development process, I have constructed the model of the development process stages that is presented in Figure 5.1. It is based on the descriptions that the interviewed experts have given about the development process at their companies. Two of the involved companies distinguish four, similar stages during their development projects, and this is what I follow in my model. The third company distinguishes an additional separate stage for the development of a prototype, which is part of the second stage in my model. The four stages of the model are: the feasibility stage, the design/prototype stage, the development/pilot run stage and the improvement/upgrading stage. The model also shows that after the detailing/pilot run stage has finished, the equipment being developed is considered to be mature. From that moment, the equipment functions as desired and is ready to be put on the market. The responsibility for the

equipment is then transferred from the development departments to the service departments in the companies. However, developments on the equipment continue after this moment in the form of new projects to improve or upgrade the equipment. Below, I give a brief introduction to each stage and to the role that maintenance aspects have in each of them. The descriptions are based on the information that the interviewees have provided about the development processes at their companies. I have combined the information from the different in-depth interviews in order to create descriptions that globally describe each stage and the role of maintenance aspects in the stages. The purpose of the descriptions is to provide a basic understanding about the development process in order to be able to correctly interpret the findings that are presented in Sections 5.2 and 5.3. To illustrate the kind of information that the interviewees have provided about the development process, I provide quotes from the in-depth interviews that are related to the description of the stages.

Figure 5.1: Model of the development process stages

Feasibility stage

In this first stage of a development project, developers generate and refine ideas for new products, upgrades on current products and solutions for problems that have arisen on the existing installed base. If necessary, they create pre-prototypes or mock-ups to test working principles and to show what the product will look like and how it will perform. They evaluate the technical and commercial feasibility of the ideas, which leads to a decision on whether or not to further develop the product, improvements or upgrades. In general, maintenance aspects do not play a major role in this stage. It is not considered to be relevant to address them specifically, since the decisions that are made in this stage do not determine the design of the equipment and thus do not have an effect on the future maintenance activities. Only when a new development project focuses particularly on the improvement of the equipment's maintenance performance, the maintenance aspects, logically, play an important role.

[Interview 7] "In first stage of a development project, service is not yet really involved. That is not a problem, because in that phase the focus lies on the definition of the needs that the company has for a new product. Issues like capacity and the demands of the market are discussed. It is still abstract what is going to be developed."

Design/prototype stage

During the design/prototype stage, developers transfer the ideas from the feasibility stage into a concrete design of the equipment. This process starts with the definition of the requirements and their specifications. Then, numerous iterations of design activities take place during which the design of the equipment is further defined. If the development project comprehends the development of a complete system, the system is decomposed into a number of sub-systems that are developed in parallel to each other. For some of these sub-systems, previous designs are re-used, while other sub-systems need to be developed from scratch. This stage ends when a decision is made to install a first version of the new equipment at a pilot site. Both for the sub-systems and the complete system, developers produce prototypes to test their functioning and performance. Maintenance aspects play a role in most of the development activities within this stage (an overview of the aspects is given in Chapter 4, Figure 4.1). Developers define specific

requirements for the equipment's maintenance related performance indicators. The process of designing the equipment concerns pro-actively thinking about, analyzing and evaluating the effect that design decisions have on the future maintenance activities and the equipment's overall performance. Also, a number of deliverables that are not part of the equipment itself, but are inextricably linked to the equipment being developed, is prepared. Examples are the maintenance scheme, maintenance manuals and maintenance diagnostic tools.

[Interview 1] "You know that when you go to a new design, a number of the building blocks of the systems need to be re-designed or newly developed. For these building blocks you must ensure that you analyze the risks. What could go wrong? The big advantage is that for all existing building blocks you know about the use of spares and about what the main issues are. For these building blocks, you can give a pretty good prediction of the availability performance."

Detailing/pilot run stage

In the detailing/pilot run stage, developers finalize the design and install a first version of the equipment at a pilot site. There, the equipment is operated and the first maintenance activities are performed. It is the first moment that developers have the possibility to analyze and evaluate the functioning of the system in a real customer environment. In general, they need to make a number of improvements to make sure that the system functions as desired, i.e. according to the specifications defined at the beginning of the design/prototype stage. At the moment that it does so, the system is considered to be mature and this development process stage ends. Also in this stage, maintenance aspects play an important role. Through operating and maintaining the system, developers get to know the wear and failure behavior of the equipment in reality and so get a better view on the maintenance that needs to be performed. If still possible, design improvements are made to solve issues that easily lead to wear or failure or that make maintenance activities difficult to perform.

[Interview 3] "When the first machine will be installed in the field, then developers also go to the field to solve problems that they had not foreseen. They solve the problems on the spot."

Improvement/upgrading stage

The improvement/upgrading stage comprises the development of improvements and upgrades on the equipment when it has already been put on the market and it is in use at various customer sites, thus during the use and support life cycle phases of the equipment. When the equipment is in use, in particular, maintenance service developers gather data and feedback on the performance of the systems in the field. They use it to analyze how the delivery of maintenance and the equipment design can be improved to better fulfill the customers' needs. If necessary, because of design flaws or when it is commercially interesting, new development projects are started to develop improvements or upgrades for the equipment. This stage ends when it is decided that no further developments will be made. Maintenance aspects often play a role in this stage, as the improvements and upgrades often have the purpose to enhance the life cycle performance of the equipment. As discussed in Section 3.2.1, effective and efficient maintenance plays an important role in achieving good performance levels. Besides the improvements on the equipment, improvements are also made on the maintenance delivery services. Maintenance service developers use the gathered data and feedback to analyze how the effectiveness and efficiency of maintenance activities can be improved.

[Interview 3] "We also have people that work on development programs to improve the systems that are not newly designed. These are already in use by the customer and lots of things are improved on these systems."

5.2 Development activities that developers perform to address maintenance aspects

This section presents the first part of the core research results with respect to RQ3: an overview of the development activities that developers perform to address maintenance aspects, including extensive descriptions of these activities. Section 5.2.1 describes the way in which the overview is constructed. Section 5.2.2 presents the overview itself. Section 5.2.3 provides overarching findings and a reflection on the literature. The overarching findings contain my interpretation of the important things that can be remarked when looking across the descriptions of the activities. These insights are based on my own reasoning about what are the most important recurring elements across the descriptions. The reflection on the literature shows how the activities that are described in the literature can be related to the developed overview that is presented in Section 5.2.2.

5.2.1 Construction of the overview

The goal of the overview is to provide insights into how maintenance aspects can be addressed, which is the topic of the first part of RQ3. The process of constructing the overview and the reasoning behind it can be described by two steps. These steps are discussed in the remainder of this section.

Step 1. Selection of activities and making descriptions

For the selection of the activities and the preparations of the descriptions of the activities, I have used the desired information from the penultimate step of the analysis of the data that was retrieved from the in-depth interviews (see Figure 3.2). During that step, the retrieved data is structured according to the questions that are supplied in Appendix 5. The relevant questions for the construction of the overview of development activities are:

Question 5a: What maintenance development activities are undertaken in a development project? Why are they undertaken?

Question 5b: What activities are undertaken to influence decisions on maintenance aspects in a development project? And why are they undertaken?

Question 5c: What activities/methods/tools are used to address maintenance aspects in the development project?

To construct the overview of activities, I have studied the information that answers these questions and I have made a list of development activities that are mentioned. Simultaneously, I have made generic descriptions of the activities and described how each of the involved companies performs the activity. The result is a table that provides an overview of the activities and the prepared descriptions. This table is the *initial* overview of development activities that developers perform to address maintenance aspects, which is part of the *initial findings* to which I refer in Section 3.1.

Table 5.1 illustrates what the table looks like. The content of the first and second columns is supplied for completeness in Appendix 6. I cannot provide the content of the other three columns because of confidentiality reasons.

Step 2. Validation and making final descriptions

In order to investigate whether the initial overview is correct and complete, I have supplied the initial overview to the experts that participated in the validations sessions, which are described in Section 3.1.3.

Activity	Generic description	Company 1	Company 2	Company 3
1. Defining and specifying requirements	In the program of requirements, specific requirements for maintenance aspects are defined. These are usually defined at the start of a project, and are, if required, adjusted based on new ideas or insights during the project. ...	...	...	...
2. Everyday discussions	In development projects...	...	...	...
3. ...	...	...	...	...

Table 5.1: Illustration of the table that is made during the process of constructing the overview of development activities that developers use to address maintenance aspects.

The experts have received a version that includes the activities, the generic description and the description that is related to their own company, i.e., the first and second columns plus the relevant one of the further three columns. Feedback on the overview was retrieved both during the sessions and afterwards via the feedback forms. The answers to the questions at the feedback forms are supplied in Appendix 8. The retrieved feedback shows the following:

- The overview is complete (see Appendix 8, answers 13 to 16)
- No suggestions are made to add or remove any of the development activities (Appendix 8, answers 13 to 16)

The feedback thus shows that the overview of activities correctly represents the development activities that developers can perform to address maintenance aspects. Therefore, the list has remained unchanged. Regarding the descriptions of the activities, I have made new descriptions based on the generic descriptions of the activities and the descriptions that were made per company (see Table 5.1). Additional insights that were retrieved after (re-)studying the information from the in-depth interviews and validation sessions are used to improve the descriptions. I have extended the descriptions by explicitly describing challenges that developers face when performing the activities. The challenges represent important issues that possibly can be addressed when a company wants to improve on the activities. They are formulated based on insights that were retrieved from studying the data that was gathered via the in-depth interviews and validation sessions. The final overview and descriptions are presented in Section 5.2.2.

5.2.2 Overview and description of the activities

This section presents the overview of development activities that developers perform to address maintenance aspects. This overview is developed to answer RQ3. Figure 5.2 presents the identified development activities and it gives an indication of the moment in the development process when they are performed. The descriptions of the activities below provide details about how developers perform these activities and discuss the main challenges that developers face to perform these activities successfully. For each activity, I also provide quotes to illustrate information that was provided by the interviewees. The overview of activities is developed based on the information that is provided by the interviewed experts from three involved companies. Therefore, it should be taken into account that the appearance of an activity within the overview does not mean that the activity is performed at all of the involved companies.

Figure 5.2: Overview of development activities that developers perform to address maintenance aspects

Activity 1. Defining and specifying requirements

Developers define and specify requirements for maintenance related performance indicators, as part of the complete set of requirements that is prepared for the equipment to be developed. The requirements are usually defined at the start of a project. As the project progresses, they are refined, specified in more detail and, if necessary, adjusted based on new ideas and insights that have emerged. Two types of requirements can be distinguished: (1) requirements related to the total time and costs for maintenance on a sub-system or the system as a whole and (2) requirements related to specific components and maintenance actions. Examples of the first type of requirements are the maximum of total required maintenance time and the maximum allowed costs of spare parts and labor during a particular period of use, e.g. a year. Examples of the second type are requirements on the minimum life time of components, the minimum time span between maintenance actions and the maximum time allowed for performing a maintenance action. The challenge is to define and specify requirements in such a way they are representative of the demands and needs of the variety in customers. As described in Section 4.3, different customers have different demands with respect to the performance of the equipment. Developers must decide whether certain requirements and specifications must be met for the equipment or that they are dealt with when the equipment is engineered for specific customer situations. For example, systems or sub-systems can be made redundant in case that it is essential that the customer's primary processes are not interrupted when the equipment fails.

[Interview 6] "When we work on developments, we prepare a user requirements specification in which also requirements are included with respect to serviceability."

Activity 2. Everyday discussions

During development projects, several people, with similar or different specializations, work together on the development of new equipment. They meet regularly, both in formal meetings and informally, and discuss the ongoing topics in the development projects. Maintenance service developers have an important role in initiating discussions about the maintenance aspects. Maintenance service developers meet regularly with equipment developers to discuss the points that need attention with respect to maintenance. The challenge is to pro-actively think about the influence that the equipment design has on maintenance. That is most difficult in the early development stages. New developments are mostly initiated to develop new technological solutions. Then, the first concern of the equipment developers is to get the system working properly. This can have the risk that maintenance aspects get less attention and are not yet discussed. At one company this challenge is faced by making a person in the core project team responsible for addressing the maintenance aspects. Also at that company, developers already make an overview of the expected maintenance on the equipment early in the development project, which forces them to think about the effect of their design choices on maintenance.

[Interview 1] “Developers are naturally inclined to focus on functionality. They sometimes reason that if you do not have something that functions, you also do not need to do any maintenance. [...] What you see is that people with more experience understand that it is important to consider maintenance during design, because if it is not considered, then you need to solve issues later on.”

Activity 3. Design reviews

Developers hold design reviews to verify the outcomes of the previous design activities and to identify the necessary improvements that still need to be made to achieve a system that performs according to the defined requirements. During such reviews, they also evaluate the equipment on its maintenance aspects. For example, developers check if the defined requirements with respect to the life time of components and the maximum time allowed for maintenance actions, are met. Maintenance service developers participate in design review meetings. They can provide feedback about issues from the field that can influence the maintenance performance and that equipment developers might not know. For example, maintenance service developers might know which failure modes occur in particular environmental conditions. As soon as a prototype is constructed, developers invite experienced service engineers to review the equipment. Because of their experience with maintaining the equipment in the field, they can provide valuable feedback on how particular aspects can be improved to make, for example, the equipment more robust and the maintenance activities easier to be performed. The challenge is to review the equipment design on its maintenance aspects early in the development process. For a good review, the input from maintenance service developers is essential. However, it can be difficult for them to understand what input is useful for equipment developers in early development stages.

[Interview 3] “Developers make the design of the equipment and regularly hold design reviews meetings. They also invite people that know about service to participate in the review meetings.”

Activity 4. Analysis of wear¹ and failure behavior

Developers analyze the wear and failure behavior of the equipment and its components, for example by making stress and deformation calculations, by performing dynamical simulations and by analyzing data of the wear and failure behavior of the installed base. They make these analyses to understand why the equipment and its components exhibit particular wear and failure behavior and how the design of the equipment or components can be improved to increase their life time. Such analyses help to substantiate choices regarding, for example, particular technologies, materials or manufacturing methods. Besides that, models of the wear and failure behavior are essential for the application of condition-based and predictive maintenance strategies. The more accurate the model of the wear and failure behavior is, the better the moment of a possible failure can be predicted and maintenance actions can be planned. The challenge is to achieve models that represent the wear and failure behavior in the real customer environment. Differences in environmental conditions and in the use, the cleaning and the maintenance of equipment cause different types of wear at different customer sites. Developers need data and information on the conditions in the field to ensure that the analyses' outcomes represent the wear and failure behavior of the equipment in the field. To deal with the different conditions, a standard approach of developers is to take the most demanding conditions as the basis for decisions on the equipment design. Adaptation to different customer environments can be done through the preparation of customized maintenance schemes.

[Interview 4] "There is a need to get, as early as possible in the development process, by means of measuring and simulating, an idea about the forces acting at particular parts."

Activity 5. Analysis of maintenance performance

Developers make analyses on the level of performance that can be achieved on the equipment's maintenance related performance indicators. In line with the two types of requirements that can be distinguished (see Activity 1), two types of performance measures are used: (1) performance measures related to the total time and costs to be made for maintenance for a sub-system or the system as a whole and (2) performance measures related to specific maintenance actions. With respect to the former developers analyze, for example, the total time required for preventive maintenance and the total cost for labor and spares to be made during a particular period of use. With respect to the latter developers analyze, for example, the time needed to replace components, the time needed to diagnose faults and the direct maintenance costs associated with such actions. They use the results to identify the most important aspects to focus on for improvement of the equipment design and for making a good calculation of the total cost of ownership. It is a challenge to make accurate estimations already early in the development process. That is especially difficult for newly developed systems or sub-systems. For systems and sub-systems that are already in use, analyses of the maintenance performance can be based on data and experience on the performance of the systems in the field. However, for newly developed systems, data and experience are not yet available. Especially, it is difficult to estimate the expected need for maintenance, as the wear and failure behavior in the real customer environment is not yet known. In such situations, developers can base their analyses, if possible, on information from suppliers who might have experience with the use of their components in

¹The term *wear* is used to refer to all possible physical mechanisms leading to degradation of components or systems that ultimately lead to failure (such as corrosion, wear and fatigue). It is not used to specifically indicate the physical mechanism of wear; see (Tinga, 2013) for an overview of failure mechanisms.

similar systems. Also, the results of testing activities (see Activity 6) are used as input for the analyses of the maintenance performance.

[Interview 1] “Based on the information that we have about the systems in the field, we know which systems have less or more problems. We know the use of spare parts and the service actions that are performed. We have people who perform analyses on this data to find the largest contributors to down time, and then we analyze the cause behind it. Is it a problem related to diagnostics? Is it a problem related to training of service engineers? [...] It could be everything, maybe it is the part itself that is the problem.”

Activity 6. Testing activities

Developers perform numerous testing activities during the development process. They use them to predict the life time of components and to detect possible problems with the functioning of the equipment already during the design/prototype development stage. Three main categories of testing activities are identified. Firstly, developers perform endurance tests to analyze the life time of individual components and sub-systems and to evaluate whether or not that is in accordance with the defined requirements. This type of testing activity is especially relevant for critical components. Also for components or sub-systems that are newly developed it is relevant to perform this type of test. For these components and sub-systems no experience is yet available on their performance in the field. Secondly, developers test the overall system performance. They test the functional performance of the equipment, for example, the technical performance and its capacity. Simultaneously they try to find out what possible problems and failures can occur during operation of the equipment. For such tests it is typical that it is not known on beforehand exactly what problems will occur. Thirdly, developers test the performance of maintenance activities. For example, they test how quickly components can be replaced and how quickly a particular fault can be diagnosed and solved. The challenge is to simulate the environmental and operational conditions in which the equipment is operated in the field. Testing centers are usually cleaner than the customer sites and the equipment is operated less roughly during tests than that it is in practice. With respect to the endurance tests, it can be difficult to accelerate use and wear of components that are continuously used when operating the equipment. With respect to the tests of the performance of maintenance activities, it can be difficult to simulate the situations in which service engineers must be able to solve a problem. In the field such situations can be extreme; also at the end of a long working day and under high time pressure, a service engineer must be able to solve a problem and get the system up and running again quickly.

[Interview 6] “We perform a lot of tests, mainly to test the life time of parts. Yes, you could also see testing as part of addressing serviceability. Also, for a product on which we currently work, we are in the stage that we have prototypes. We perform tests on the functioning of the complete system, but we also have test set-ups for parts of the system. [...] You test the life time of these particular parts by means of such a separate set-up.”

Activity 7. Maintenance service design activities

During the development process, developers prepare a number of maintenance deliverables, such as maintenance schemes, maintenance manuals, tools to diagnose faults and initial spare parts lists (see the maintenance service design aspects in Figure 4.1). In general, developers prepare the maintenance deliverables at the end of the design/prototype development stage. To prepare the maintenance scheme two companies have developed their own tools that support in doing this systematically. These tools are discussed in Section 5.3.2 under *Factor 6. Availability and usability of methods/tools to support addressing maintenance aspects*. During the development/pilot run and improvement/upgrading development stages, maintenance service developers make improvements on the maintenance deliverables and on the maintenance delivery services. The

challenge is to prepare the maintenance deliverables already during the design/prototype stages, in parallel to the design of the equipment. That could be difficult, because it is not the main concern of developers at that moment. However, they indicate that it is useful, as it forces them to think about the effect that design decisions have on the maintenance that is required and how easy it can be performed. The approaches discussed in Section 4.2 address a number of examples of how the equipment design affects the need for and execution of maintenance.

[Interview 2] “During the development process, we prepare service deliverables. You need to arrange spares, you need a maintenance scheme, you need to provide explanation, which means that you also develop training for service engineers to ensure that there is a certain level of knowledge in the field.”

Activity 8. Making improvements during the pilot run

As discussed in Section 5.1, during the development/pilot run stage, developers install a first version of the equipment at a pilot site. There it is operated and maintained for the first time. During this stage, developers analyze and test the equipment and evaluate if it performs according to the defined requirements. If required, they make (minor) changes to the design of the equipment. During the development/pilot run stage, developers need to solve numerous, so-called, infant mortalities; failures that occur on new equipment only. Also, developers test the correctness and completeness of maintenance deliverables and, if necessary, improve them. The challenge is to achieve a system that performs according to its performance specifications as quickly as possible. In the development/pilot run stage, problems often must be solved under time pressure. Solutions that require changes to elementary design choices are often too time-consuming and costly to implement. Therefore, the best solutions cannot always be implemented.

[Interview 2] “For a new design we know that the desired performance is not directly met, because you will find things that need to be improved.”

Activity 9. Developing upgrades/improvements during the use and support life cycle phases

As discussed in Section 5.1, during the use and support life cycle phases, companies start new projects to solve design problems and to develop upgrades that have the purpose to enhance the performance of the equipment. To define what to focus on, developers gather data and feedback about the performance of the equipment that is installed in the field (see also Activity 10). Also, they use the data and feedback to analyze how the maintenance scheme can be improved and, in case that it is the responsibility of the equipment manufacturer, to improve the maintenance delivery services. The challenge is to select which improvements and upgrades to develop. Together with other stakeholders in the company, developers must determine which improvements or upgrades have the greatest potential to improve the satisfaction of the customer and are worth spending time on.

[Interview 7] “We also have the products that are already in use, of which a number are already installed in the field. Such products are constantly subject to improvements. We have a group that discusses the issues from the field about what really needs to be improved. Then we know which things should be better addressed in new projects.”

Activity 10. Gathering and analysis of data and feedback

Developers gather feedback and data about the performance of the equipment, from the moment that it is installed in the field. Developers use it to get insights into the reasons why the equipment fails, why the equipment performs better or worse than expected, why more or less maintenance is required than expected and why maintenance actions are easy or difficult to perform. They use it for the improvement of the maintenance service design and in development projects of new

equipment. To gather data, developers use data-gathering functionalities that are built-in into the systems and reports that service departments make about the maintenance actions that they have performed. Regarding gathering feedback, four ways are identified in which developers retrieve it. Firstly, developers get feedback when they are working on the equipment in the field themselves. Secondly, service engineers, sales employees or other employees who work in the field or have contact with customers or users, share their feedback pro-actively with equipment developers. Thirdly, developers have access to feedback systems that companies use to report problems that have occurred and the maintenance activities that are performed. Fourthly, developers attend meetings in which people who work in the field or who have contact with the field, discuss the issues that are noticed by service engineers and customers. The challenge is to ensure that both equipment and maintenance service developers receive data and feedback in a usable format and that the employees who can provide it, share it pro-actively. Employees in the field, who can provide data and feedback, know the best how the data and feedback should be interpreted. For equipment and maintenance service developers, it can be difficult and time consuming to find out what exactly can be learnt from the data and the retrieved feedback.

[Interview 5] “We have three feedback loops, of which the one for mechanical issues is the most important one. The other two are for feedback related to mechatronics and the engineering projects. Regarding the loop for mechanical issues, we have a monthly meeting during which we discuss the submitted problem reports.”

5.2.3 Overarching findings and reflection on the literature

Taking a look across the activities shows that developers use many ways to address maintenance aspects and that they face a number of challenges to do that successfully. Recurring elements in the descriptions of the activities are the need for explicitly addressing the effect of design choices on maintenance early in a development project and the difficulty of doing that. The need for doing that arises from the fact that design choices that are made early in the process can have a considerable impact on the maintenance performance that can be achieved later on. The difficulty arises from the fact that, early in the development process, it is not yet known which maintenance actions are required and/or how much maintenance is needed in a real customer environment. That makes it difficult to analyze and evaluate the effect of design decisions on the maintenance performance that can be achieved. This is especially valid for newly developed systems and sub-systems. For such systems no data and experience are available from similar systems that are already operated in the field, which is necessary to make meaningful analyses on the wear and failure behavior.

The literature that is described in Section 2.2 also includes activities that are relevant to perform in order to address maintenance aspects. Blanchard & Fabrycky (2014) and Takata et al. (2004) explicitly list activities that need to be performed to address maintenance aspects during the life cycle of a product or system. Appendix 10 shows how the activities can be related to the activities of the developed overview that is presented in Section 5.2.2. It shows that the developed overview covers all except one of the activities that are mentioned in the literature. Also, there are differences between the overviews. These are the following. The overview provided by Blanchard & Fabrycky (2014) describes the activities at a more detailed level. The overview by Takata et al. (2004) is more general and only gives a general idea about the activities that need to be performed. The added value of the developed overview that I present in this chapter is that it not only describes the activities that need to be performed, but that it also provides details about how developers can perform these activities and the challenges that they face. The overview thus not only gives a list of activities that need to be performed. It also provides insights on which specific tasks developers can improve or for which supported can be introduced or developed.

5.3 Factors that affect whether maintenance aspects are addressed successfully

This section presents the second part of the core research results with respect to RQ3: an overview of the factors that affect whether maintenance aspects are addressed successfully. Section 5.3.1 describes the way in which the overview is constructed. Section 5.3.2 presents the overview itself. Section 5.3.3 provides overarching findings and a reflection on the literature. The overarching findings are core insights that emerge when taking a look across the different factors. These insights are based on my own reasoning about how the factors can be grouped. The reflection on the literature shows how the factors that are described in the literature can be related to the developed overview that is presented in Section 5.3.2.

5.3.1 Construction of the overview

The goal of the overview is to provide insights into the factors that affect whether maintenance aspects are successfully addressed. The process of constructing the overview and the reasoning behind it can be described by two steps. These steps are discussed in the remainder of this section. The steps are similar to the steps of the construction of the overview of development activities that developers perform to address maintenance aspects, described in Section 5.2.1.

Step 1. Selection of factors and making descriptions

For the selection of the factors and for making the descriptions of the factors, I have used the desired information from the penultimate step of the analysis of the data that was retrieved from the in-depth interviews (see Figure 3.2). During that step, the retrieved data is structured according to the questions that are supplied in Appendix 5. The relevant question for the construction of the overview of the factors is:

Question 4e: What actors and factors do contribute to or hinder successfully addressing maintenance aspects in a development project?

To construct the overview of factors, I have studied the information that answers this question and made a list of the factors that are discussed. Simultaneously, I have made generic descriptions of the factors and, per company, a description about why the factors are considered to be important. The result is a table that provides an overview of the factors and the descriptions. This table is the *initial* overview of factors that affect whether maintenance aspects are addressed successfully, which is part of the *initial findings* to which I refer in Section 3.1. Table 5.2 illustrates what the table looks like. The content of the first and second columns is supplied for completeness in Appendix 6. I cannot provide the content of the other three columns because of confidentiality reasons.

Step 2. Validation and making final descriptions

In order to investigate whether the initial overview is correct and complete, I have supplied the initial overviews to the experts that participated in the validations sessions, which are described in Section 3.1.3. The experts have received a version that includes the factors, the generic description and the descriptions that are related to their own company, i.e. the first and second columns plus the relevant one of the further three columns. Feedback on the overview was retrieved both during the sessions and afterwards via the feedback forms. The answers to the questions at the feedback forms are supplied in Appendix 8.

Activity	Generic description	Company 1	Company 2	Company 3
1. Knowledge on maintenance aspects	The basis for making good decisions is having good knowledge on the topic of interest. Knowledge that is particularly relevant with respect to the ...	...	...	...
2. Availability and quality of data	During the life time of the equipment, data can be gathered about ...	...	...	...
3. ...	...	...	...	...

Table 5.2: Illustration of the table that is made during the process of constructing the overview of factors that affect whether maintenance aspects are addressed successfully.

The retrieved feedback shows the following:

- No suggestions are made to remove any of the activities (see Appendix 8, Answers 18 to 21).
- Suggestions are made to add factors (see Appendix 8, Answers 19 to 21).

Based on the feedback, the overview is improved. Two factors are added, namely *Factor 4. Knowledge on the existing installed base* and *Factor 9. The extent to which addressing maintenance aspects is embedded in the development process* (see Table 5.3). The suggestion to add financial / economical influence (see Appendix 8, Answer 19) is not adopted, because this is considered to be part of *Factor 8. Launch timing*. Regarding the descriptions of the factors, I have made new descriptions based on the content of both the generic descriptions of the activities and the descriptions per company (see Table 5.2). Additional insights that were retrieved after (re-) studying the data gathered from the in-depth interviews and validation sessions are used to improve the descriptions. The final overview and descriptions are presented in Section 5.3.2.

5.3.2 Overview and descriptions of the factors

This section presents the developed overview of factors that affect whether maintenance aspects are successfully addressed. Table 5.2 shows the fourteen specific factors that are identified and which activities they affect the most. The accompanying descriptions explain the factors. They provide insights on why the factors are relevant to consider and include concrete actions that can be undertaken to improve on the factors. The list of factors is developed based on the information that is provided by the interviewed experts from the three involved companies. For each factor, I also provide quotes to illustrate information that was provided by the interviewees or participants in the validation sessions.

Factor 1. Knowledge on maintenance aspects

The basis for addressing maintenance aspects successfully, is that developers have a profound understanding of how decisions on the equipment design affect the maintenance activities and maintenance performance. In particular, developers consider knowledge with respect to the following two topics to be relevant. Firstly, it concerns knowledge of the interrelations between equipment design, maintenance service design and the service environment, and their mutual influence on the maintenance performance.

No.	Factor	Related activities
1	Knowledge on maintenance aspects	All
2	Availability and quality of data	4, 5, 10
3	Availability and quality of feedback	2, 3, 4, 5, 10
4	Knowledge on the existing installed base	4, 5, 10
5	Quality of definition and use of performance indicators and requirements	3, 5
6	Availability and usability of methods/tools to support addressing maintenance aspects	2, 5, 7
7	Timing of addressing maintenance aspects	All
8	Launch timing	8
9	The extent to which addressing maintenance aspects is embedded in the development process	All
10	Supplier involvement	4, 5
11	Customer involvement	1, 10
12	Quality of communication	1, 2, 3, 10
13	Individual quality and skills of developers	All
14	Company organizational and cultural factors	All

Table 5.3: Overview of the identified factors that affect whether addressing maintenance aspects is done successfully and the related development activities (the numbers in the columns refer to the descriptions in Section 5.2.2)

For example, developers must understand how equipment and maintenance diagnostics tools can be designed in such a way that a service engineer in the field, under all circumstances, can easily diagnose faults and solve problems, without the help of second or third line engineers. Secondly, it concerns knowledge on the interrelations between the equipment design and the conditions in which the equipment is operated, and their mutual influence on the maintenance performance. For example, developers must understand how wear and failure behavior relates to particular environmental and operational conditions in order to develop an effective and efficient maintenance strategy. If developers have good knowledge on such topics, they are more likely to automatically make good decisions on the equipment design with respect to the maintenance aspects.

[Interview 2] “A developer should be able to take care of everything related to the design of the equipment and should know the factory and the service environment.”

Factor 2. Availability and quality of data

Developers require data on maintenance and performance of the equipment in the field to analyze how the equipment design and applied maintenance strategies can be improved. They need data on wear and failure behavior, the maintenance activities that are performed and the equipment’s performance. When a company has a large installed base, developers can apply statistical analysis to the data to get insight into the variation of the equipment’s performance at different customers’ sites. To have data available, it needs to be gathered during the equipment’s life time by the developers, maintenance providers or users. However, it can be difficult to retrieve data. A reason can be that it is hard to retrieve it from the equipment. Another reason can be that users make restrictions on the retrieval of data. To make the data useful, it is especially important to register it in combination with the environmental and operational conditions in which the equipment is used. Also, the data should be provided in an easily usable format to the

equipment developers, to avoid unnecessary pre-processing of the data before the developers can use it as input for their analyses.

[Interview 6] “Getting reliable information about the performance of the system and the real failure behavior has the most added-value for me at the moment. [...] You need information about which parts wear out fast.”

Factor 3. Availability and quality of feedback

Besides the need for data, developers indicate that feedback from the field is important to understand how the design of the equipment can be improved. Data as discussed under *Factor 2. Availability and quality of data* concerns the raw data that is available on the maintenance performance of the equipment in the field. Feedback can enrich the value of such data, as it provides insight into, for example, which data is relevant for a particular development project and how the data should be interpreted. Employees that work in, or regularly have contact with the field, can provide insights into issues that equipment developers might not know or not think about when they develop new equipment. Examples of such issues are: specific failure modes that only occur under specific environmental or operational conditions, the reasons behind performing maintenance actions and the reasons behind equipment failures. Different causes of failures, such as human errors, design flaws and wear problems, require different design improvements to solve them. Other valuable feedback that people from the field can provide, is feedback on the ease of performing maintenance activities and on the aspects that are the most important to focus on in order to improve the user’s primary processes. Developers emphasize the importance of getting feedback early in the development process. Later on in the development process, it can be time consuming and costly to make changes to the equipment design. Also, like with data, to make feedback useful it should be provided to developers in an easily usable format and include explanations on why it is relevant to do something with it.

[Interview 3] “Equipment developers know a lot about the product that they develop, but there are circumstances in which the product fails about which you have never thought.”

Factor 4. Knowledge on the existing installed base

To enhance the quality and usability of the data and feedback that is gathered and retrieved, developers indicate the importance of having an overview of and knowledge on the installed base. Such an overview must contain information on what type of equipment is installed at which customer site, including its version. It should also include information on which components are used and the components versions, suppliers and production batches. In addition to that, developers indicate that it is desired to have an overview of the characteristics of the environmental and operational conditions at each customer site. Having a complete overview on the installed base and the related environmental and operational conditions, enables developers to relate particular wear and failure behavior and maintenance performance to, for example, equipment versions, suppliers, manufacturing issues or environmental conditions.

[Feedback via feedback form (see Appendix 8, Answer 11)] “To be able to have a good feedback loop, you need to know exactly which system is installed at which customer site (which product version, which component versions, which component suppliers, etcetera).”

Factor 5. Quality of definition and use of performance indicators and requirements

Developers consider proper definition and use of performance indicators and requirements of key importance for addressing the maintenance aspects. Performance indicators and requirements reflect the development objectives and, thus, determine on which aspects developers have to focus during a development project. Regarding their definition, the performance indicators and requirements should properly represent both the demand and wishes

of (potential) customers and include the aspects that might be important for the companies' (future) business activities. With respect to the former, for example, requirements and specifications for maintenance costs can be expressed in different ways: as a budget for the total of maintenance costs over a particular period, as a percentage of the price of the equipment and as a percentage of the number of products produced or processed. With respect to the company's business activities, it can be important to define requirements for, for example, the upgradeability of the equipment or the features that the equipment should have to register performance data. The importance of the maintenance related performance indicators and requirements can differ between projects. Therefore, it should be clear what the relative importance of the maintenance related performance indicators is in a particular development project. It affects whether or not attention is given to maintenance aspects.

[Interview 2] "We, for example, have defined availability as one of important key performance indicators [...] However, from the perspective of the customer, the number of products per day might be the most important to focus on."

Factor 6. Availability and usability of methods/tools to support addressing maintenance aspects

Developers indicate that particular methods and tools help them to systematically address maintenance aspects. Two companies have developed their own methods. One company uses a method to classify the maintenance items according to the maintenance strategy that will be applied. This is done at the end of the design/prototype development stage, by equipment and maintenance service developers together. Subsequently, the maintenance service developers analyze the risk of following a particular strategy for each item and use it as basis for the preparation of the maintenance scheme. The developers consider the method to be very useful, as it helps them to explicitly list the required maintenance actions. Also, they indicate that the method is easily usable and not time consuming to apply. The other company uses so-called availability matrices to analyze the availability performance of the equipment. For each sub-system, developers identify the expected corrective and preventive maintenance actions, the time required for performing these actions and the costs to be made for labor and spares. This information is used to calculate the total expected downtime and costs per sub-system. Based on the overview of the sub-systems, maintenance service developers generate an overview for the complete system. Developers prepare initial versions of the overviews already early in the design/prototype stage. They use them to evaluate if the equipment performs according to the defined requirements on availability and costs and to identify for which sub-systems or components improvements are required, to prevent high down time and/or high maintenance costs. The developers consider the use of the matrices to be very useful, as it supports them in systematically reviewing the equipment and finding the most important aspects to focus on for improvement already early in the development process. Furthermore, they consider the matrices as a useful tool for guiding discussions about maintenance aspects. To enable their use, printed versions of the matrices hang on the wall in the company's offices. Besides the methods that the companies have developed themselves, developers at the involved companies also find FMEA (Moubray, 1997, pp. 54-89) useful. Some developers use them, others say that they should do that. These methods help them in identifying the possible causes of equipment failures and their impact already during the design/prototype stage. Using FMEA can also help equipment developers in getting useful feedback from employees from other departments.

[Interview 5] "Our method is to classify all maintenance items into groups. The first group are the consumables, the second group the break down parts and the other groups are the parts for which a preventive maintenance strategy will be followed. [...] The method that we use now may look very quick and dirty, but it is nevertheless based on practice and not labor-intensive."

Factor 7. Timing of addressing maintenance aspects

Maintenance aspects are, implicitly and explicitly, addressed throughout the whole development process. In particular, developers emphasize the importance of addressing aspects that are related to the equipment design already in the early development stages. They indicate that the possible effect of the design choices in the early stages on the maintenance performance should be considered. Examples of design choices that are made, are choices on materials, used technologies, system structure and modularity and redundancy levels. Early in the development process, it is relatively easy to make changes to the equipment design. In later stages that is time-consuming and costly. Then, a change on the equipment design also requires changes of, for example, the already prepared drawing packages, methods of manufacturing and operation and maintenance manuals. Developers indicate that it is worth spending time to analyze the effect of design choices on maintenance in early development stages: already when developers must choose between different concept solutions. The timing of addressing maintenance aspects is also discussed in Section 4.3.2.

[Interview 4] “Early in a development project, when you can still go in all directions, you can easily change a design. [...] Later on in the development project, when you have a pilot run at a customer site, you cannot make big design changes anymore because that has a large impact at the whole organization.”

Factor 8. Launch timing

The decision on the moment that companies launch the new equipment to the market is generally based on a trade-off between the necessity of bringing the equipment to the market and the completeness of the product. On the one hand, it is important to bring the product to the market as early as possible, to be earlier than competitors. On the other hand, there is the risk to put a product on the market that is not yet completed; for example, bringing a product to the market that functions correctly, but of which the maintenance performance specifications are not yet met. That could have undesired consequences. For example, problems can occur in a later life cycle phase, which then need to be solved by costly design changes. Also, extra preventive maintenance can be needed to compensate for design flaws, which increases the down time of the equipment. Finally, it could lead to more variety of the installed base in the field, which makes it more complicated to manage and organize the maintenance activities. Developers emphasize the importance of making a well-considered decision on the launch timing of the equipment. If the equipment is not completely finished yet when it is launched to the market, a plan should be made for solving the remaining issues in the field.

[Interview 7] “For new developments, you want to keep the development time as short as possible. You want to go to the market to show and sell your product. What you do not want is that you keep improving your product and that you finally are not able to sell it, while you have made lots of costs for the development. But when is the product good enough? Different stakeholders that can have their own opinion.[...] The service department, that is responsible for the maintenance during a long time, is the most critical on the product, its maintainability and issues like the availability of components in the future.”

Factor 9. The extent to which addressing maintenance aspects is embedded in the development process

Making the addressing of maintenance aspects part of the prescribed development process of a company, ensures that developers explicitly address them. It can be achieved through, for example, making it mandatory to perform analyses on the maintenance performance, reviewing the equipment on its maintenance aspects during design reviews and performing tests on maintenance activities. Also, developers consider it as useful to include the development of

maintenance deliverables as standard activities within the development process. When deliverables, such as maintenance schemes, maintenance instructions and spare parts lists must already be developed during the design/prototype development stage, developers automatically think about the effect that their design decisions have on maintenance.

[Feedback via feedback form (see Appendix 8, Answer 11)] “Suggestion to add the factor that certain maintenance service deliverables, among which the preventive maintenance scheme, are standard deliverables of the development process.”

Factor 10. Supplier involvement

The equipment being developed consists for a large part of components and technologies that are developed by suppliers. To make a good estimations of the wear and failure behavior and of the required maintenance on the equipment, developers need the knowledge and expertise of their suppliers. For example, developers need to know the wear and failure behavior of the suppliers' components when they are integrated in the equipment. The components' wear and failure behavior is likely to be different in a situation that the component is constantly used or in a situation that it is switched on and off continuously. Also, for the suppliers it is important that they are involved in the development activities of the equipment manufacturers. They need feedback on the performance of their components in order to be able to improve them. Another reason why developers consider supplier involvement to be important, is that developers need to know about the future availability of the components. The suppliers' policies regarding the production of the components determines whether or not the components will keep being available during the long life times of the equipment.

[Interview 3] “We need reliable data from our suppliers that make parts, because only then we can make a reliable prediction when it concerns the availability. [...] To give an example, a particular component is made by a supplier. When I ask about the time this component last, then they could say that it lasts a particular number of hours. But what does that mean? The life time when it is constantly used? In case that the component is switched on and off continuously when it is installed in our equipment, the life time is different.”

Factor 11. Customer involvement

Involvement of customers is relevant for the definition of the performance indicators and requirements and with respect to the gathering and analysis of data and feedback. Regarding the definition of performance indicators and requirements, developers emphasize the importance of having a good understanding of the demands and wishes of (potential) customers. Involving the customers helps them to determine what is important for the customer and, so, to define the performance indicators and requirements accordingly. Regarding the gathering and analysis of data and feedback, developers mention their dependence on the customers. In many cases, the customers operate and maintain the equipment. This means that they have the knowledge on the equipment's wear and failure behavior, the required maintenance and the performance levels achieved, which is important information for developers to know how they can improve the equipment. In development projects, employees from the service department who have contact with customers on a regular basis, participate in project meetings to share the knowledge retrieved from customers.

[Interview 7] “We discuss with customers about which key performance indicators are important for them. [...] We need to understand the customer and the customer must understand us so that we get a key performance indicator that is acceptable for both.”

Factor 12. Quality of communication

Good communication between people in development projects is essential for making optimal use of each other's expertise. With respect to addressing maintenance aspects, developers indicate that, for others than equipment developers, it can be difficult to discuss and to provide feedback on the equipment design already early in the development project. To enhance the quality of communication about maintenance aspects, developers emphasize that it is important for employees from different departments to understand the essentials of the topics being discussed. Specifically, this means, that equipment developers understand the basics of maintenance and, for example, maintenance service developers have basic technical knowledge to understand the equipment design. Also, developers point out that the use of something concrete, such as 3D-models and prototypes, enhances the quality of communication on maintenance aspects. Particularly, with respect to design reviews, the use of the defined requirements as way to guide discussions, is mentioned as an important means to ensure that maintenance aspects are properly addressed.

[Interview 6] "In a project team all relevant departments are usually represented, also someone from the service department. We had the idea that this would ensure that the relevant service issues would be discussed in time during a development project. However, in practice it turns out that it for people from other departments can be difficult to make a useful contribution early in the development process. [...] Later on, when the equipment is installed in the field, then it is easy for them to provide feedback."

Factor 13. Individual quality and skills of developers

The quality and skills of individual developers are important factors when it comes to addressing maintenance aspects. It affects, for example, if and when developers address maintenance aspects and how they communicate about them. Regarding equipment developers, the empirical study indicates that differences exist between new and experienced equipment developers. In general, experienced developers are more aware of the importance of addressing maintenance aspects and of how to do that. Companies use courses and trainings on maintenance, visits to customer sites and providing the possibility to work together with service engineers in the field to enhance the quality and skills of equipment developers. Regarding maintenance service developers, the research indicates the importance of having technical knowledge and skills to communicate maintenance issues to equipment developers (as also discussed at Factor 12) as being important. Good knowledge and skills also are important to develop mutual understanding between different stakeholders in development projects. This stimulates people to work together when that is necessary to achieve good development results.

[Interview 1] "One of the things that we do is that we, within our training programs, include training on maintenance. Such training programs are organized."

Factor 14. Company organizational and cultural factors

With respect to company organizational and cultural factors, the empirical study shows three things. Firstly, the organizational structure of a company can influence the way in which equipment developers and maintenance service developers communicate about maintenance aspects. For example, developers indicate that having separate departments for new equipment development and for improvements on current equipment, can easily cause that data and feedback on maintenance aspects only reaches one of the departments. Also, developers indicate that physical separation of equipment development and service development departments can lead to less attention for maintenance aspects, as it causes maintenance aspects to be less discussed in the everyday discussions. Secondly, developers indicate that imbedded ways of working in companies can hinder the use of new and more systematic ways to address maintenance aspects.

Thirdly, developers indicate that the importance that company and project management attach to maintenance aspects, strongly affects how much effort is put into addressing the maintenance aspects during a development project.

[Interview 4] “We have two engineering departments, one for new developments and one for the existing products in our portfolio, which deals with customer specific modifications and updates of particular products. When something is learnt at a customer site, then feedback is provided, but it usually only reaches the department for new developments. Especially feedback about wear problems is shared. We now try to ensure that the feedback is also shared with the other department.”

5.3.3 Overarching findings and reflection on the literature

Section 5.3.2, shows that a variety of factors affects whether maintenance aspects are addressed successfully. These are factors of importance across all development activities. By taking a closer look at these factors, three core insights emerge. Firstly, the importance that is given to maintenance aspects in development projects largely affects whether or not maintenance aspects are explicitly addressed. The importance is reflected in the extent to which requirements are defined for the maintenance related performance indicators and the extent to which they are used by developers to evaluate the equipment design (Factor 5). Furthermore, it is reflected by the extent to which developers explicitly address the required maintenance and the preparation of maintenance deliverables, for example through the use of methods to indicate the required maintenance already early in the development process (Factors 6, 7 and 9). Finally, it is partly reflected in the more organizational issues that influence whether or not maintenance aspects are addressed successfully (Factors 8 and 14). Secondly, the knowledge on maintenance aspects in development teams and the knowledge and skills of individual developers to address them is of key importance to successfully address the maintenance aspects (Factors 1, 12 and 13). Thirdly, there is a strong dependence on data and feedback from the field for making meaningful analyses on the equipment’s wear and failure behavior and maintenance performance (Factors 2, 3 and 4). For retrieving it, developers also depend on stakeholders outside the companies, such as customers and suppliers (Factors 10 and 11).

The literature that is described in Section 2.2.2 also describes factors and other elements that affect addressing maintenance related aspects. Table 2.2 lists them. However, the literature in which they are described does not explicitly focus on the development of a list of factors that affect whether maintenance aspects are addressed successfully. Therefore, it is not possible to make a direct comparison between the research results and the presented literature. It can be said that the factors and other elements that are mentioned in the described literature are covered in the developed overview. Table 5.4 shows how they can be related to the developed overview that is presented in this section. Two factors of the developed overview, *Factor 4. Knowledge on the existing installed base* and *Factor 8. Launch timing*, are not mentioned in the table. The added value of the developed overview that I present in this chapter is twofold. Firstly, it provides a complete overview of all factors that experts consider to be relevant. Secondly, the accompanying descriptions explain in detail how the factors affect whether maintenance aspects are addressed successfully. This provides insights about very specific actions that can be undertaken to improve on addressing maintenance aspects.

5.4 Lessons learned regarding how maintenance aspects can be addressed successfully

The previous two sections clearly show that in order to address maintenance aspects, developers need to perform several development activities throughout the whole development process. A variety of factors affects how successful the maintenance aspects are addressed in these activities. The activities and factors together are the elements that can be used to describe a company's capability on addressing maintenance aspects. Within the activities, developers address the maintenance aspects that are presented and discussed in Chapter 4. The current section discusses the main lesson learned regarding how maintenance aspects can be addressed successfully by means of three key issues. These are formulated by means of taking a look across the results that are presented in Chapter 4 and the research results that are presented in the current chapter. The key issues are based on my own reasoning about the main lessons that can be learnt from the research results.

Firstly, all stakeholders in a development project should have a clear and shared vision on the relative importance of addressing the maintenance aspects.

If the relative importance is clear, developers can focus their efforts on those aspects that are most important in a particular development project. The relative priority of development objectives is also mentioned by Krishnan & Ulrich (2001, p. 7) as one of the relevant decisions in setting up a development project. The relative importance of maintenance aspects may differ between development projects. It should be assessed with respect to the overall development objectives that need to be fulfilled within the budget and time available. Therefore, a good definition of the performance indicators that represent the overall development objective, represented by the system level performance aspects in Figure 4.1, is of key importance. As the project progresses, requirements for specific individual components and maintenance actions can be derived from the defined indicators. The item level performance aspects in Figure 4.1 represent the performance measures that are relevant to use. When the performance indicators are properly defined, they can and should be used to evaluate the outcomes of development activities and to define which development efforts need to be made. Although the definition of performance indicators sounds easy, it may be difficult to find performance indicators that represent the demands and wishes of various customers. The insights that are provided in Section 4.3.1, Section 5.2.2 - Activity 1 and Section 5.3.2 - Factor 5 are related to this key issue.

Secondly, it is of key importance that developers, already early in a development project, address the effect that the decisions on the equipment design have on maintenance. Early in a development project, developers make decisions on the aspects that are related to the equipment design. These are the equipment design aspects, scenario related equipment design aspects and equipment & maintenance service design aspects in Figure 4.1. Decisions on these aspects can have a large effect on the need for maintenance, the ease with which maintenance activities can be performed and the maintenance strategies that can be applied. Not properly addressing these aspect can have the consequence that later on in the development project, or when the equipment is installed in the field, problems occur or performance levels are not met. If then changes are required they are likely to be time-consuming and costly to implement. To improve the performance of maintenance during the life time of the equipment, developers can address the aspects listed as maintenance service design aspect in Figure 4.1. It is useful to already think about them during the development of the equipment, as this helps to proactively consider the influence of the equipment design on maintenance. The insights that are provided in Section 4.3.2, Section 5.2.2 - Activity 2, Section 5.3.2 - Factor 7 are related to this key issue.

Source	Elements of importance
Antioico et al. (2008)	<p>Type of research: empirical research to identify organizational and communication factors that affect relative product and service characteristics.</p> <p>Important courses of action for manufacturing companies are related to the following three topics:</p> <ul style="list-style-type: none"> - Managing service feedback. [related to Factor 3] - Information-sharing norms. [related to Factor 12] - Communication channel and content. [related to Factor 12]
Goffin & New (2001)	<p>Type of research: empirical study on how to address customer support in new product development.</p> <p>Identified best practices for addressing customer support in new product development are:</p> <ul style="list-style-type: none"> - Closely involving customer support experts in new product development. [related to Factor 11] - Performing a comprehensive evaluation of support needs at the design stage and setting suitable design goals. [related to Factors 5 and 7] - Using data management systems to monitor all aspects of field support. [related to Factors 2 and 3] - Having top management that recognizes the importance of customer support. [related to Factor 14] - Using customer support to gain a competitive advantage and to increase revenues. [related to Factor 9]
Markeset & Kumar (2003b)	<p>Type of research: empirical study on the integration of reliability, availability, maintainability and supportability (RAMS) and risk analysis in the work processes of a manufacturing company.</p> <p>Element of the RAMS integration process are:</p> <ul style="list-style-type: none"> - RAMS, LCC and risk analysis tools and methods. [related to Factor 6] - RAMS and risk analysis information and data. [related to Factors 2 and 3] - Data bases and information systems. [related to Factors 2 and 3] - Organizational management and support. [related to factor 14] - Motivation, cooperation, teamwork, knowledge, creativity and innovation. [related to Factor 1, 12 and 13] - Communication and interface with customers, suppliers and distributors. [related to Factor 10 and 11] - Product characteristic evaluation. [related to Factor 5] - Project management and control. [related to Factor 14] - Quality assurance and control. [related to factor 3]
Rapaccini et al. (2013)	<p>Type of research: empirical research to develop a model to assess the maturity of new service development (NSD) processes</p> <p>The areas of importance to assess a company's maturity on NSD and their elements are:</p> <ul style="list-style-type: none"> - Organizational approach: relevance of NSD; roles; and management practices. [related to Factor 14] - Resources: budget; tools and methods; skills. [related to Factors 1, 6 and 13] - Customers, suppliers and other stakeholders: customers; suppliers and other stakeholders. [related to Factor 10 and 11] - Performance management: feedback systems (satisfaction, acceptance and impact of new services); and key performance indicators. [related to Factors 2 and 5]
Tan et al. (2010)	<p>Type of research: empirical study on how two manufacturing companies approach services.</p> <p>The identified challenge to provide integrated solutions and services is:</p> <ul style="list-style-type: none"> - Feedback loop from service to product design: the organizational separation of product-oriented and service-oriented activities makes it challenging to share design relevant information, because of differences in business motivation, culture and language. [related to Factors 12 and 14]

Table 5.4: Elements mentioned in the literature that affect addressing maintenance related aspects and the activities or factors to which they are related.

Thirdly, quantitative analysis of the maintenance performance is desired. Quantitative analyses give developers profound insights into the performance levels that can be achieved. Also, they can help to define which aspects are the most important to focus on in order to improve the maintenance performance. In particular, it is important to have a profound understanding of the wear and failure behavior of the equipment. When making analyses, developers need to consider the elements of the environment in which the equipment is operated and maintained, represented by the scenario aspects in Figure 4.1.

These elements can strongly influence which performance levels can be achieved and may be different for various customer sites. Addressing them properly requires collaboration with customers, suppliers and possibly other stakeholders. The insights that are provided in Section 4.3.1, Section 5.2.2 - Activities 4 and 5, Section 5.3.2 - Factors 2, 3 and 4 are related to this key issue.

5.5 Conclusion

This chapter shows that developers perform several development activities throughout whole the development process in which they address maintenance aspects. Also, it shows that a number of factors affect whether these maintenance aspects are addressed successfully. This chapter provides two overviews in which, respectively, the development activities and factors are listed and described.

The development activities that developers perform to address maintenance aspects are: (1) defining and specifying requirements, (2) everyday discussions, (3) design reviews, (4) analyses of wear and failure behavior, (5) analyses of maintenance performance, (6) testing activities, (7) maintenance service design activities, (8) making improvements during the pilot run, (9) developing upgrades/improvements during the use and support life cycle phases and (10) feedback and data gathering and analysis. The main differences between the overall approaches of the companies are reflected in (1) the extent to which particular persons in a development team are dedicated to address the maintenance aspects and (2) the extent to which developers explicitly identify the required maintenance during the design/prototype stage and (3) the methods and tools that are used. Taking a look across the description of the activities shows the need for explicitly addressing the effect of design choices on maintenance early in a development project and the difficulty of doing that. In the early stages of the development process choices are made on the equipment design that can have a considerable impact on the maintenance performance that can be achieved. However, it is difficult to already analyze and evaluate the effect of the design choices as it is not yet known which maintenance actions are required and/or how much maintenance is needed in a real customer environment.

Fourteen factors have been identified that affect whether the maintenance aspects are addressed successfully. These are the following: (1) knowledge on maintenance aspects, (2) availability and quality of data, (3) availability and quality of feedback, (4) knowledge on the existing installed base, (5) quality of definition and use of performance indicators and requirements, (6) availability and usability of methods/tools to support addressing maintenance aspects, (7) timing of addressing maintenance aspects, (8) launch timing, (9) the extent to which addressing maintenance aspects is embedded in the development process, (10) supplier involvement, (11) customer involvement, (12) quality of communication, (13) individual quality and skills of developers, (14) company organizational and cultural aspects. Three core insights emerge when taking a closer look at the factors. Firstly, the importance that is given to maintenance aspects in development projects strongly affects whether or not maintenance aspects are explicitly addressed. Secondly, the knowledge of project teams and the knowledge and skills of individual

developers is of key importance to ensure that maintenance aspects are addressed successfully. And thirdly, there is a strong dependence on data and feedback from the field for making meaningful analyses on the equipment's wear and failure behavior and maintenance performance.

Three key issues are formulated to summarize the main lessons learned about how maintenance aspects can be addressed successfully. Firstly, it is essential to have a clear and shared vision on the relative importance of the maintenance aspects between all stakeholders in a development project. Secondly, developers should already early in the development process address the effect of the equipment design on the maintenance performance that can be achieved. Thirdly, quantitative analyses of the maintenance performance are desired to get profound insight into how the equipment design and maintenance service design can be improved.

6 Support for addressing maintenance aspects

This chapter presents the results of the Prescriptive Study and thus answers Research Question 4 (RQ4): *How can developers be supported in successfully addressing maintenance aspects in industrial equipment development projects?*

The objective of the Prescriptive Study is to use the understanding obtained from Descriptive Study I to propose support to developers that helps them to address the maintenance aspects. A complete and systematic Prescriptive Study contains five steps: (1) task clarification, (2) conceptualization, (3) elaboration, (4) realization and (5) evaluation (Blessing & Chakrabarti, 2009, p. 146). The *initial* Prescriptive Study performed for the research presented in this thesis (see Section 1.6) contains the first two steps and elements of the remaining three steps. Inspired by the results of Descriptive Study I, I propose three tools that are useful to support addressing maintenance aspects in industrial equipment development projects:

Support 1. *Overview of relevant maintenance aspects, development activities and factors*

Support 2. *Maintenance performance calculation matrix*

Support 3. *A set of design-for-maintenance guidelines*

The first support consists of the overviews that are developed in Descriptive Study I. These overviews are developed in such a way that they can be used for decisions making in development projects. The second support is based on a tool that is used by one of the companies that was involved in the research. The third does not directly follow from Descriptive Study I. Instead, it is developed because the results of Descriptive Study I show that the basis for addressing maintenance aspects is that developers have good technical knowledge on how the maintenance performance of the equipment can be affected. In particular, *Factor 1. Knowledge on maintenance aspects* and *Factor 13. Individual knowledge and skills of developers*, which are described in Section 5.3.2, explain this.

The chapter starts by discussing the insights obtained from the Descriptive Study I on which support could be useful for developers to address maintenance aspects. This reflects the results of the task clarification step. Then, Sections 6.2, 6.3 and 6.4 describe the three types of support, respectively. For each support, I give a description and motivate why it can be useful, explain the use of the support and the key factors that are addressed by using it, and discuss the evaluation. These sections represent the results of the conceptualization and, especially for Support 3, also the results of the elaboration and realization steps. Finally, Section 6.4 presents the conclusion.

6.1 Insights obtained from the Descriptive Study

The results of the Descriptive Study I give a profound understanding of the factors that are important to address in order to support developers in addressing the maintenance aspects in a development project. The diagram in Figure 6.1 graphically represents how supporting the factors should ultimately lead to more competitive equipment and service offerings. A simple version of this diagram is introduced in Section 1.5.

Figure 6.1: Diagram illustrating the intended effect of Support 1, Support 2 and Support 3 (the numbers of the activities and factors refer to the descriptions in Sections 5.2.2 and 5.3.2)

The support to be used or to be developed should address one or more of the factors that affect whether maintenance aspects are successfully addressed. These factors are described in Section 5.3.2. They are the *key factors* to consider when a company wants to improve on addressing the maintenance aspects.

The activities and factors together are the important elements that describe a company's capability in addressing maintenance aspects. An improved capability should improve the quality of design decisions with respect to the maintenance aspects. As discussed in Section 4.2, making good design decisions with respect to the maintenance aspects requires that developers consider the equipment design, the maintenance service design and the elements of the environment in which the equipment is operated and maintained (represented in Figure 6.1 by the scenario aspects) in an integrated way. Making better design decisions on maintenance aspects means that the maintenance performance of the equipment will be improved, which ultimately leads to equipment and service offerings that are more competitive.

As discussed above, possible support to be developed, should address the key factors. Depending on which key factors a company wants to address in order to improve on addressing maintenance aspects, one can think of different types of support. Companies should decide on what the most important factors are to improve on in order to improve their products and/or development process. Overall, support should especially be focused on the improvement of addressing maintenance aspects in the early development stages. As discussed in Section 5.2.3, explicitly addressing the effect of design choices on maintenance early in the development process is considered to be most important and the most difficult to do. The three tools that I propose in this chapter can be used in the early stages of a development project. The tools have in common that they are meant to provide overview and to systematically address the maintenance aspects. This is desired, because Descriptive Study I has made clear that addressing maintenance aspects comprises many different aspects that are both related to the equipment, the maintenance service and the environment in which they are used (see Chapter 4). It is easy to overlook relevant aspects, especially in the early development stages. One of the insights that emerged from taking a close look at the identified key factors, is that the knowledge of development teams and individual developers is of key importance to address maintenance aspects successfully (see Section 5.3.2). However, individual developers alone do not have the complete overview of all issues that might be relevant to consider.

The three tools that I propose, support developers by providing overview at three different levels of product development. Support 1 deals with the strategic level. It gives developers an overview of what aspects can be considered in a new development project. Support 2 addresses the tactical level. It supports developers in keeping track of the relevant maintenance related performance indicators throughout the development project. Support 3 addresses the operational level by supporting the concrete design tasks that developers need to perform. As discussed in the introduction of this chapter, Support 1 and 2 follow from Descriptive Study I. Support 3 is developed because Descriptive Study I shows that the basis of addressing maintenance aspects is that developers have good technical knowledge on how the maintenance performance of the equipment can be improved.

6.2 Support I – Overview of relevant maintenance aspects, activities and factors

Support 1 consists of the overviews that are developed to answer RQ2 and RQ3. Specifically, these are: (1) the model of relevant maintenance aspects presented in Figure 4.1, (2) the overview of development activities to address maintenance aspects, described in Section 5.2.2 and (3) the overview of factors that affect whether addressing maintenance aspects is done successfully, described in Section 5.3.2.

Use of the support and key factors addressed

Developers can use the overviews to discuss and identify which are the most important aspects to focus on in a development project and which activities and factors should be considered in order to address these aspects successfully. This can be done, for example, at the start of a new equipment development project or when discussing which improvements or upgrades can be developed for the existing installed base. The overview can also be used for guiding design reviews and everyday discussions. If necessary, a company can adapt the overviews to its own individual situation.

As indicated in Figure 6.1, the key factors that are directly addressed by this support, are:

- Factor 7. Timing of addressing maintenance aspects
The model of relevant maintenance aspects provides an overview of the aspects to be addressed in a development project. At the least, the use of the overviews ensures that developers consider addressing particular maintenance aspects early in the development project and that they think about the activities that they need to perform to do that successfully.
- Factor 12. Quality of communication
The overviews provide concrete topics to discuss about. Therefore, they can stimulate discussions around a given specific aspect. That likely enhances the quality of the discussions that developers have with each other and with other stakeholders.
- Factor 13. Quality and skill of individual developers
For developers who are not yet familiar with maintenance aspects, the overviews provide the topics that are relevant to think about. New ideas might arise when taking a look at the overviews.

The use of the overviews to address these factors stimulates that maintenance aspects are more explicitly discussed in the everyday discussions and during design reviews. Discussions about the maintenance aspects enhance the quality of decisions that developers make with respect to them.

Evaluation of the support

As described in Section 3.1.2, the content of the support is evaluated in the empirical study. For further development of the support, it should be investigated how it can be implemented best. I expect that the key prerequisite is that it is provided in an easily usable format to the developers. That is possible, for example, through printing the overviews on paper, development of a poster and providing them in a digital format so that the overviews can be presented at a presentation screen. The usability of the support is not yet evaluated. Evaluation of the support should in the first place focus on whether or not practitioners use it. To investigate this, the support can be distributed among various developers at industrial equipment manufacturers. After a while, by using surveys or interviews, it is possible to determine whether or not they have used the overviews and the reasons behind this.

6.3 Support 2 – Maintenance performance calculation matrix

Support 2 is a maintenance performance calculation matrix. The idea for this support is based on the fact that developers consider quantitative analysis of the maintenance performance to be desired to make good decisions with respect to the maintenance aspects (see Section 5.2.2, Activity 4). Also, one of the involved companies uses a similar tool in its development process (see Section 5.3.2, Factor 6). Especially the way in which it can be used, makes this support useful already in the early development stages, but also in later stages.

Description of the support

The tool is a matrix in which all possible maintenance actions can be listed in combination with their performance on the relevant item level performance indicators (see Figure 4.1). Figure 6.2 illustrates such a matrix. Developers can use a spreadsheet to prepare it. Within the matrix, both the corrective and preventive maintenance actions are listed. For each of the actions the performance on the relevant performance indicators can be filled in. Within the matrix in Figure 6.2, these are:

- The frequency that a maintenance action is required in a particular period, for example per year.
- The time needed for performing a maintenance action.
 - For corrective actions: the time to diagnose, the time to repair or replace a component and the time to recover the equipment.
 - For preventive actions: the time to inspect, the time to service and the time to recover.
- The cost of spares.
- The cost of labor.

Companies can adapt the matrix in such a way that it includes the relevant performance indicators for the system that is being developed. When completely filled in, the matrix gives (1) an overview of the time required for each action and the related costs and (2) the total time required for maintenance and the related costs for the complete system.

The tool helps companies to apply an information driven design approach for addressing the maintenance aspects. As Holman et al. (2003) discuss, the implementation of such an approach is the next step that companies should take to raise their development activities to a new level, after adopting standardized development processes. It focuses on better information management to boost the product development performance. The key of the approach is that development decisions are based on the information that is available. Developers continually react to it in order to determine which development efforts must be made to create a successful product effectively, in less time and with fewer resources. The tool aids developers in keeping track of the information that developers need in order to make decisions with respect to the maintenance aspects. The description of the use of the tool, which is presented below, explains how that can be done.

Use of the support and key factors addressed

Developers can use the tool for the evaluation of the maintenance performance of the equipment during the whole development process that is represented in Section 5.1. As discussed in Section 5.2.2 (see the description of Activity 1), developers use two types of performance measures, namely (1) performance measures related to the total time and costs to be made for maintenance for a sub-system or the system as a whole and (2) performance measures related to specific maintenance actions.

System A

Corrective Actions (CA)

Frequency (per year)	Time per action (hours)			Time per year (hours)	Costs per action (Euro)		Cost per year (Euro)
	Time to diagnose	Time to repair/replace	Time to recover		Cost of spares	Cost of labor	
2	0.2	0.2	0.1	1.0	150	75	450
0.5	0.5	0.2	0.1	0.75	500	250	375
...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...

Preventive Actions (PA)

Maintenance Actions (PA)	Time to				Time to recover	Total maintenance time:	...	Total maintenance cost:	...
	inspect	service	recovery	total					
PA 1	...	...	...	...	...	...	...	...	...
PA 2	...	...	...	...	...	...	...	...	...
PA 3	...	...	...	...	...	...	...	...	...
PA ...	...	...	...	...	...	...	...	...	...
PA ...	...	...	...	...	...	...	...	...	...
Total maintenance time:						Total maintenance cost:		...	

Figure 6.2: Illustration of a maintenance performance calculation matrix

The level of performance on both types of the performance indicators becomes clear when the matrix is filled in. Developers can evaluate whether or not the desired levels of performance are met and specifically identify for which maintenance actions improvements are required. If, for example, the time needed for a corrective maintenance action is higher than allowed, developers know on which specific part of the action (for corrective maintenance: diagnostics, repair/replacement or recovery) they should focus in order to improve the performance. If the total maintenance costs are higher than allowed, developers can easily identify which maintenance actions cause these costs.

Although the supports may seem easy to use, there are three things to consider. Firstly, a proper evaluation is only possible when reliable data is available on the frequency of maintenance actions and the time required to perform them when the system is installed in the field. In addition to that, as the model of relevant maintenance aspect shows (see Figure 4.1), the performance on these indicators is related to the environment in which the system is operated and maintained. That means that the performance might be different for each customer site and that specific performance measures must be related to particular environmental and/or operational conditions. Secondly, industrial equipment may contain many components which makes it a time-consuming activity to analyze the levels of performance for each performance indicator. The advantage of making such analyses should be a trade-off against the costs for gathering and analyzing the data in order to retrieve a reliable overview. Thirdly, at the start of a development project the design is not yet concrete and all the possible maintenance actions are not yet known. In particular that is the case for sub-systems that will be completely new and the ones that are changed. Only for the components and sub-systems that are re-used from a previous design, the data is available. At least, when it is gathered during the use and support life cycle phase of the systems that are installed in the field. For newly developed sub-systems and components, developers need data from suppliers on the failure rates of the equipment or need to perform their own analyses and testing activities to get insight into the required maintenance actions and the time needed to perform them.

Overall, in order to make the tool useful in the early development stages, it is particularly important that developers indicate what the reliability is of data that is filled in and if data is related to particular conditions in which the systems are operated and maintained. When that is clear, developers can, firstly, use the overview to identify (1) which aspects of the components and sub-systems that are already used in existing systems need attention in order to improve the maintenance performance. Secondly, they also can use the overview to identify the components and sub-systems of which the effect on the maintenance performance is not yet known and for which further analysis is required to determine if there is a risk for high maintenance time or costs. Based on that information, developers can determine which the most important aspects are to focus on in order to improve the equipment in such way that the desired performance levels are met.

As depicted in Figure 6.1, the key factors that are addressed by using this support are the following:

- Factor 3. Quality of feedback.
The matrix provides a complete overview of all maintenance actions. Therefore, the feedback that, for example, maintenance service developers give to equipment developers, can be specifically related to a particular maintenance action. The equipment developers then exactly know which topic the feedback addresses.

- Factor 5. Quality of definition and use of performance indicators and requirements.

The use of such a matrix ensures that the equipment is evaluated on the relevant performance indicators. However, it should be ensured that the used performance indicators are in line with the desired overall performance of the equipment. By using the example in Figure 6.1, the focus will be on the improvement of the total maintenance time and costs. However, it might also be important to evaluate the cost per produced product in order to decide whether or not further improvement of the equipment on its maintenance aspects is desired.

- Factor 7. Timing of addressing maintenance aspects.
The use of such a tool from the moment that developers start to determine the equipment design ensures that already early in the development process developers think about the effect of their design decisions on the maintenance performance.
- Factor 9. The extent to which addressing maintenance aspects is embedded in the development process.
Proper implementation of such a tool means that it has to be used in the development process and thus that the maintenance aspects are addressed.
- Factor 12. Quality of communication
By providing an overview of the maintenance activities and their performance indicators, developers have concrete issues to discuss. However, developers should be careful that the discussions do not concentrate on the correctness of the numbers. Especially the reasoning behind the numbers gives insight into how the equipment design can be improved.

The overall effect of addressing these factors is that already early in the development process, developers think about the effect of the equipment design on the maintenance performance. The use of the tool enables that developers have an initial overview of the possible maintenance actions already early in the development process. It can be used to identify which sub-systems and components are the most important to focus on in order to ensure that the desired overall system performance will be met.

Evaluation of the support

One of the involved companies already has implemented the use of a similar tool in its development process. To enable its use, developers hang versions of the matrices on the offices' walls. To understand the exact effect of using such matrices, it might be interesting to study how developers in that company use the matrices on a daily basis and the effect that their use has on the design decisions that are made. Also, it would be interesting to implement the tool in a companies that do not yet use it and also do not use something similar. That can provide a better understanding of the effect that such a tool has on the way that developers address maintenance aspects and in which situations it is worth using it.

6.4 Support 3 – Set of design-for-maintenance guidelines¹

Support 3 is a set of design-for-maintenance guidelines. These guidelines focus on the *equipment design aspects* within the model of relevant maintenance aspects (see Figure 4.1). The main part of the support is a leaflet with design guidelines on how reliability, maintainability and

¹ The content of this section is partly adopted from Mulder et al. (2014)

supportability of industrial equipment can be enhanced. The leaflet is supplied in Appendix 11. A booklet (Mulder et al., 2012) accompanies this leaflet. The booklet explains the guidelines and gives, for each guideline, three sub-areas in which it can be applied. The description of each sub-area is accompanied with an illustration that shows the results of applying, or not applying, the guideline.

Description of the support

The development of this support is based on the idea to provide a wide range of design-for-maintenance ideas that can be considered when developing industrial equipment. The use of a set of guidelines to do this, is based on two characteristics that guidelines have (Chiu & Okudan Kremer, 2011). Firstly, guidelines represent explicit knowledge that can be used to address specific design objectives. In the context of this research, this objective is to enhance the equipment's performance on its maintenance related performance indicators. Secondly, guidelines are easy to incorporate into the current way of working and can support multiple design activities without the need for changing the used design procedures. This makes implementation in practice easy. During the development of the set of guidelines, both the content and the way in which it is presented are explicitly addressed.

Regarding the content, it is important that the guidelines give solution directions that help to enhance the equipment's properties that directly influence the performance of the maintenance activities, i.e. the product's reliability, maintainability and supportability. In addition to that, it is important that they are useful for various companies, as my research aims to support addressing maintenance aspects for various types of industrial equipment. As also discussed in Section 2.1, various literature in the field of product design and engineering addresses which aspects should be addressed. Table 6.1 shows the literature that is used as knowledge source for the development of the set of guidelines.

Literature	Type of guidelines			
	General design guidelines	Design-for-maintenance guidelines	Product related guidelines	Guidelines from other fields of study
Dhillon (1999)		X		
Gardner & Sheldon (1995)		X	X	
Imrhan (1992)		X		
Knezevic (1997)		X		
Lidwell et al. (2010)	X			X
Pahl et al. (2007)	X	X		X
Boothroyd et al. (2011)			X	X
Woodson et al. (1994)				X

Table 6.1: Literature used as knowledge source for composing the set of guidelines

Both guidelines from the literature on design-for-maintenance and guidelines from related fields are used. The way in which the guidelines are formulated should stimulate that developers think about the reason to apply it. Each of the guidelines consists of two parts. The upper part of the guidelines gives a prescriptive statement about how to improve the reliability, maintainability or supportability of the equipment. The lower part provides the rationale behind the statement or

an example of how it can be applied. With respect to the way in which the guidelines are presented, several possibilities exist, such as a poster, a digital format and the leaflet that is used. The prerequisites are that the support should be usable without the need for a change of the existing development process and that it could be used as addition to, or can be incorporated into, the current working approaches of developers.

Use of the support and key factors addressed

The set of guidelines is in the first place meant as a tool to start discussions about different design possibilities. The leaflet makes this possible, as it can be easily used during the everyday discussions between people in a development project. It can be easily distributed among employees and can draw attention for the maintenance aspects when it is on a developer's desk. Other areas of application could be during design reviews and for updating maintainability checklists that a company might already use. Similar to Support 1, companies are encouraged to think about developing an own version, with guidelines that are specifically relevant for their equipment.

As shown in Figure 6.1, the key factors that are addressed by Support 3 are:

- Factor 7. Timing of addressing maintenance aspects
The use of the set of guidelines in the early stages of the development process ensures that the maintenance aspects are in the mind of developers. This stimulates that developers automatically think about the effect of their design decisions on maintenance.
- Factor 12. Quality of communication
The set of guidelines provides concrete topics to discuss, which stimulates that discussions are concentrated around specific topics.
- Factor 13. Quality and skills of individual developers
The leaflet provides an overview of the various topics that developers can think about and it might contain ideas that an individual developer has not considered yet.

Through addressing these key factors, the set of guidelines helps to explicitly address maintenance aspects in the everyday discussing and design reviews.

Evaluation of the support

The content of the guidelines is evaluated in two workshops with industrial partners. Also, I have seen one example, Thales (2013), in which a company has used the set of guidelines as basis for developing its own set of guidelines. The company has implemented it by means of a poster. However, it is not yet possible to draw strong conclusions on the extent to which this support is used and leads to an improvement of the design decisions that developers make with respect to the maintenance aspects. A thorough evaluation study would be necessary to investigate this. Since the support (the leaflet and the booklet) is distributed among a considerable number of practitioners, this could be done by investigating whether or not those practitioners have used it or not.

6.5 Conclusion

The results of the Descriptive Study give a profound understanding of the key factors that should be supported in order to address maintenance aspects successfully. In this chapter, three types of support are proposed that provide overview and stimulate designers to explicitly address the maintenance aspects during development projects. The three tools support the developers at three different levels of product development: the strategic, tactical and operational level, respectively.

The first tool consists of the overviews of relevant maintenance aspects, the development activities that are performed to address them and the factors affecting whether or not that is successfully done. This support aims to stimulate developers to explicitly discuss the maintenance aspects when a new equipment development project is started. The second tool is a maintenance performance calculation matrix. It supports the quantitative analysis of the maintenance performance and helps developers to systematically discuss and identify the most important aspects to focus on in a development project. Especially for this tool the advantage of implementing it needs to be a trade-off against the time and costs needed for doing it properly. The third tool is a set of design-for-maintenance guidelines that particularly focuses on aspects of the equipment design. Similar to the first tool, it aids in discussing the maintenance aspects explicitly. The three tools have in common that they provide a clear overview to developers on what aspects are relevant to address. The tools stimulate that developers think about maintenance aspects. Also, they help developers to systematically identify which are the most important aspects to focus on in order to develop the competitive equipment within the available development time and budget. The second and third tool are already implemented in practice. Therefore, it is already possible to evaluate whether or not their implementation has an effect on the success of addressing the maintenance aspects.

7 Conclusion

In this dissertation, I present a design research study that is conducted to develop an overview of the maintenance aspects that are relevant to address in industrial equipment development projects and to propose how these aspects can be addressed successfully. The external and internal research goals were formulated in Section 1.5 as follows:

External research goal. To support developers in addressing maintenance aspects.

Internal research goal. To develop knowledge on the relevant maintenance aspects to be addressed in development projects, on how these aspects can be addressed successfully and on how developers can be supported to do this.

To achieve the research goals, a Descriptive Study I and a Prescriptive Study were performed. The results of Descriptive Study I provide a thorough understanding of the maintenance aspects to be addressed in development projects. It supports developers by giving a holistic overview of and thorough insights into the maintenance aspects that are relevant to address, the development activities that developers perform to address maintenance aspects and the factors that affect whether these are addressed successfully. The Prescriptive Study proposes three types of tools that are useful for developers to address maintenance aspects in industrial equipment development projects in practice. This final chapter presents the conclusions in Section 7.1, the discussion in Section 7.2 and a number of directions for further research in Section 7.3.

7.1 Conclusion

The starting point of the research was the assumption that the understanding in companies on how maintenance aspects can be successfully addressed, can provide thorough insights into how developers can be supported in addressing the aspects. Below, I discuss the most important insights that the research has given. Firstly, I provide answers to the four research questions that have guided the research. Secondly, an overall conclusion is given.

Research Question 1. *What is the relevance of addressing maintenance aspects in industrial equipment development projects?*

This first research question is meant to verify that addressing the maintenance aspects is relevant for the companies that are involved in the research and to provide context for understanding the results of the other research questions. The research confirms that addressing maintenance aspects is relevant at the involved companies. It shows that addressing the maintenance aspects is important to (1) to meet the technical performance and productivity specifications of the equipment, (2) to enhance the marketability of the equipment, (3) to fulfill the customers' demand regarding the equipment's life cycle performance and (4) to ensure that the equipment manufacturers can deliver competitive maintenance services. These four reasons show that addressing maintenance aspects is important both to provide competitive equipment solutions and to develop solutions in which products and services are integrated. Equipment manufacturers have different customers, each one having different demands and wishes. Therefore, they need to address the maintenance aspects in such a way that they can offer competitive equipment and/or services to a range of customers.

Research Question 2. What are the relevant maintenance aspects to be addressed in industrial equipment development projects?

Both the literature and the empirical study show that a lot of knowledge is available about the maintenance aspects that are important to be addressed. This research has resulted in a model that gives an overview of the relevant aspects and orders them in three categories, according to the way in which developers use them to make design decisions: the model distinguishes *performance aspects*, *scenario aspects* and *equipment design / maintenance service design aspects* as the three main categories of aspects that need to be addressed. Performance aspects represent the maintenance related performance indicators that developers should define and use to evaluate the outcome of the development activities. It is relevant that developers define the desired levels of performance on these indicators and use them to evaluate the performance of the equipment and/or maintenance service that is developed. Scenario aspects are the elements of the environment that affect the levels of performance that can be achieved. They are outside the direct range of influence of developers, but developers must anticipate them when making design decisions. Equipment and maintenance service design aspects representing the characteristics and properties of the equipment, the maintenance deliverables and the elements of the maintenance delivery services. The research shows that properly addressing the maintenance aspects requires that developers consider the interrelations between the equipment design, the maintenance service design and the elements of the environment in which the system is operated and maintained. The developed model gives a complete overview of the aspects that developers can consider to address during a development project. However, it is important to consider that not all aspects should or can always be addressed. The relevance of addressing particular aspect is related to the goal of the development project and the stage in which a development project is.

Research Question 3. How can maintenance aspects be addressed in industrial equipment development projects and what factors affect whether this is successfully done?

The research shows that maintenance aspects need to be addressed throughout all stages of a development process and that a number of factors affects whether the aspects are addressed successfully. The research has resulted in two overviews that list (1) the ten activities that developers perform to address maintenance aspects and (2) the fourteen factors that affect whether the aspects are addressed successfully, including extensive descriptions of the activities and factors.

The ten development activities are: (1) defining and specifying requirements, (2) everyday discussions, (3) design reviews, (4) analyses of wear and failure behavior, (5) analyses of maintenance performance, (6) testing activities, (7) maintenance service design activities, (8) making improvements during the pilot run, (9) developing upgrades and improvements during the use and support life cycle phases and (10) gathering and analysis of data and feedback. This research shows that in the early stages of a product development project it is most important and most challenging to address maintenance aspects successfully. It is especially challenging to explicitly analyze and evaluate the effect of equipment design decisions on the performance of maintenance.

The fourteen factors that have been identified are: (1) knowledge on maintenance aspects, (2) availability and quality of data, (3) availability and quality of feedback, (4) knowledge on the existing installed base, (5) quality of definition and use of performance indicators and requirements, (6) availability and usability of methods/tools to support addressing maintenance aspects, (7) timing of addressing maintenance aspects, (8) launch timing, (9) the extent to which addressing maintenance aspects is embedded in the development process, (10) supplier involvement, (11) customer involvement, (12) quality of communication, (13) individual quality

and skills of developers and (14) company organizational and cultural aspects. Taking an overarching look at these factors provides three core insights. Firstly, the importance that is given to maintenance aspects strongly affects whether or not maintenance aspects are explicitly addressed. Secondly, the knowledge of project teams and the knowledge and skills of individual developers are of key importance to ensure that maintenance aspects are addressed and that good design decisions are made. Thirdly, there is a strong dependence on data and feedback from the field to conduct meaningful analyses.

Research Question 4. How can developers be supported in addressing maintenance aspects in industrial equipment development projects?

The ten activities and fourteen factors that I have found by answering Research Question 3, are the elements that can be used to describe a company's capability to address maintenance aspects. The fourteen factors are the key factors to consider when a company wants to improve on addressing the maintenance aspects. Therefore, support to be implemented or used should focus on one or more of these factors. Depending on the factors upon which a company wants to improve, different support is possible. I propose three tools that are meant to provide an overview to developers and to help them in addressing the different aspects systematically. The three tools provide support on three different levels of product development, namely the strategic, tactical and operational level. For the strategic level, I propose the use of the overviews of relevant maintenance aspects, activities and factors, which are part of the result of this research. The use of the overviews can stimulate discussions explicitly addressing maintenance aspects when a new development project is started. It supports developers in selecting which aspects, activities and factors are most important to focus on during the project. For the tactical level, a maintenance performance calculation matrix is suggested. It supports in keeping track of the relevant maintenance related performance indicators throughout the development project. Also, it aids in the systematic identification of which aspects need particular attention in order to achieve the desired levels of performance. For the operational level, the use of a set of design-for-maintenance guidelines that focuses on the various aspects of the equipment design is recommended. It supports developers in explicitly addressing the maintenance aspects during the concrete design tasks that they need to perform. Support should be properly implemented to have the desired effect. The first and third tool can be implemented without much efforts. For successful implementation of the second tool, it is required to make considerable efforts in retrieving reliable performance data. Whether or not to implement such a tool should be a trade-off between the advantage of implementing it and the cost of a proper implementation.

Overall conclusion

This research makes clear that a lot of knowledge exist with respect to the maintenance aspects that are relevant to address and about how these can be addressed successfully. It also shows that a lot of knowledge is implicit and that it was not yet synthesized in a comprehensive and holistic way. Therefore, the main contributions of the research presented in this thesis are the following:

1. It has made the implicit knowledge of developers explicit.
2. It gives a comprehensive and holistic overview of relevant maintenance aspects and of how they can be addressed successfully in development projects.

The knowledge is organized in a model and two overviews that enable it to be used as design support. The model and the overviews provide a starting point for companies that want to address the maintenance aspects more explicitly. Also, the research gives a starting point for further development of design support that fits the needs of developers in industry.

Based on the results of the research related to Research Questions 2 and 3, I have formulated three key issues to summarize the main lessons learned regarding how maintenance aspects can

be addressed successfully. Firstly, the starting point is that all stakeholders in a development project have a clear and shared vision on the relative importance of addressing maintenance aspects in order to develop competitive equipment and/or service solutions. If that is clear, the performance indicators and requirements related to maintenance can be defined accordingly and should be used to evaluate the outcomes of the development activities. Secondly, it is of key importance that, already early in a development project, developers explicitly address the effect that decisions on the equipment design have on maintenance. The equipment design affects to a large extent which levels of performance can be achieved. If, later on, changes are required, then they are likely to be time-consuming and costly to implement. Thirdly, quantitative analysis of the maintenance performance is desired. This gives a thorough understanding about whether or not the desired performance levels can be achieved and which improvements are required to meet the overall objectives in a development project.

Finally, it is clear that in order to successfully address the maintenance aspects, several design activities need to be performed that are integrated throughout the whole development process. It is challenging to do this properly. Many aspects need to be addressed, different demands and wishes of customers need to be taken into account, different conditions in which the equipment is used and maintained must be considered and also aspects other than maintenance aspects need attention. The main lesson from this research is that profound knowledge is required to make good design decisions and that individual developers do not have an overview of all things that might be relevant to address for making good decisions. Individual developers need the knowledge and insights from other stakeholders, from both inside the company and from outside the company. Good cooperation between all of them is of key importance to use the existing knowledge among the various stakeholders to its full potential. Cooperation is necessary to be able to develop competitive equipment and service solutions effectively and efficiently.

7.2 Discussion

In this section, I reflect on the research approaches that I have used and I discuss their effect on the validity of the research results. I first discuss the use of DRM as research approach and the methods that are used in the empirical study to gather data: in-depth interviews and validation sessions. I next discuss the generalizability and the limitations of the research.

DRM

The use of DRM has been valuable to structure the research. The methodology clearly distinguishes between descriptive and prescriptive research stages. The explicit separation of these stages ensures that the researcher profoundly studies the existing insights in the literature and the situation in practice before starting the development of support. In this research, it turned out that both the literature and developers in practice did not have a clear answer on whether or not support would be desired. An iterative process of data analysis appeared to be necessary to get a complete view on the topic and to have a solid basis for developing support.

Data collection methods: in-depth interviews and validation sessions

Within the empirical study, two methods of collecting data are used: in-depth interviews and validation sessions. The use of in-depth interviews as a means to gather data has been proven very valuable. It made it possible to explore the tacit knowledge of the interviewed developers in-depth. During the interviews, the relevant topics could be discussed from different perspectives and relations between topics could be made. For example, development activities could be discussed in relation with the relevant maintenance aspects. A limitation of using in-depth interviews is the limited number of interviewees that can be included in order to keep profound data analysis possible within the limited time span of a research project. However, the limited number of

interviewees appeared not to be a problem for answering the research questions. The most important factors for retrieving useful data are the level of expertise of the interviewees and the time that is available for holding an interview. It was experienced that during interviews both the interviewer and the interviewees needed time to get familiar with the topic of the interview. As the interview progressed, the research topic could be explored better. The validation sessions gave the possibility to retrieve insights from a larger number of professionals. The sessions themselves gave a general idea of the correctness of the findings. However, they did not provide many new insights into the research topic. The most useful comments were retrieved via the feedback forms that were returned afterwards. It seems that, to properly study the topic of the research, it is desirable to use methods that give people time to reflect on the topics that are discussed.

Generalizability of the research results

The research results are based on the information that experts from three companies in the industrial equipment manufacturing industry have provided. Therefore, it cannot be directly concluded that the research results also provide a complete and correct overview of the relevant maintenance aspects, the development activities and the factors that affect whether maintenance aspect are addressed successfully at other companies that develop and provide industrial equipment. However, it is very likely that the results are also applicable to such companies: The information that was provided via the validation sessions (see Section 3.1.3) shows that the developed overviews provide an almost correct and complete overview for each of the three companies. Further investigation is needed to investigate if the developed model and overview are representative for companies in the industrial equipment manufacturing industry in general. Whether the results are also applicable to companies that provide other types of technical systems also needs further investigation. I expect that the main findings will be similar for companies that provide systems for which maintenance is important to achieve a good life cycle performance, such as the *transportable, mobile* technical systems in Figure 1.1 (aircrafts, ships and trains). On a more detailed level, it is likely that differences exist with respect to, for example, the specific maintenance aspects that are relevant to address.

The way in which I have described the findings likely is also suitable for research into other type of aspects to be addressed in development projects, such as manufacturing or sustainability. This research shows that providing overviews of the relevant maintenance aspects, development activities and factors is a very suitable way to provide a holistic view on the research topic. However, this way of structuring and describing the findings does not only apply to research about maintenance aspects. Likely, it is also a good way to provide an overview of other relevant aspects and the way in which these aspects can be addressed successfully.

Limitations of the research

There are three main limitations inherent to this research. The first relates to the relatively small number of experts that were involved in the research. As discussed above, under *Data collection methods: in-depth interviews and validation sessions*, this was due to the choice of using in-depth interviews as data collection method. In order to be able to conclude that the results are valid for industrial equipment development projects in general, it is desired that a validation study is performed in which a larger number of experts, from a larger number of companies, is involved. The second limitation is that the use and the effect of the proposed design support, which is described in Sections 6.2 to 6.4, is not investigated in real development projects. Such an evaluation is not performed because it is out of scope for an *initial Prescriptive Study*, as I have performed (see Section 1.6). In future research, the Prescriptive Study can be completed in order to investigate whether the proposed tools have the intended effect. A third limitation is the way in which the empirical study is set up. Because of the lack of an appropriate theoretical model at the start of the research project, the formulated questions of the interview guide did not cover all

relevant topics to be discussed with the experts, which is also discussed in Section 3.1.2. Therefore, two steps of data analysis were required. The first step was to find the important topics and questions to be answered in order to make a structured description of the current understanding in companies about how to address maintenance aspects. That step has resulted in the questions that are listed in Appendix 5. Subsequently, a second step was necessary in which the retrieved data was analyzed according to the listed questions. Ideally, the empirical study would have been set up around these questions from the start. Therefore, I would recommend to use these questions as basis for an empirical study when conducting similar research, rather than those used in the interview guide (see Appendix 2).

7.3 Further research

This section provides a number of directions for further research on how developers can be supported to address maintenance aspects. Firstly, I discuss how the research that is presented in this thesis can be continued. Secondly, I discuss how the integration of knowledge from other fields of research can help to further develop the understanding of how maintenance aspects can be addressed. I consider this very important, as there is a lot of knowledge available that can be better used.

Continuation of the research

The results of research that is presented in this thesis are based on the practices of three industrial equipment manufacturing companies in Dutch industry. As discussed in Section 7.2, it is desired to investigate to which extent the results can be generalized and applied to other types of technical systems and their development processes. This could be investigated by conducting similar studies at other companies. I expect that the relevant aspects will be similar, but that the overview can be made more complete. For other types of technical systems, aspect might be relevant that are of less importance for industrial equipment.

It would also be interesting to focus on the similarities and differences between companies and industries with respect to the aspects that are relevant to address. This is related to the relationship between the topics that are addressed in Research Questions 1 and 2. In the current research, the topic of Research Question 1 is only investigated to a limited extent, in order to provide context to the results of Research Questions 2 and 3. To be able to further improve the results of the research, a profound understanding is required on the interrelations between all of the three research questions: *why* is it relevant to address maintenance aspects, *what* aspects are relevant to address and *how* can they be addressed best? The current research especially gives understanding on the relationships between the *what* and the *how* questions. The relationship between the first and second research question could be addressed through investigating which aspects are addressed in which development projects. Then, the relevance of aspects can be related to, for example, particular equipment, industries and business strategies. This then can be used to develop a model that gives developers an overview of the things to consider when thinking about giving attention to particular aspects in a development project. Such an overview could be a supplement to the model of relevant maintenance aspects that is presented in Figure 4.1. It could be a strong tool to support developers in exploring the solution space for new equipment and service offerings and thus to determine which aspects are the most interesting to focus on in a particular development project. To set up such research, I would recommend to also incorporate the sales, marketing and/or business development functions of the companies. They can probably provide more in-depth insights into the reasons why particular aspects can be important to address for a companies' business.

With respect to the how question, I consider it as most promising to focus on how to support the provision of good feedback. The research clearly shows that knowledge and insights from different stakeholders are of key importance to address the maintenance aspects successfully. However, the research also shows that it is difficult to ensure that useful feedback reaches the equipment developers at the right moment. Whether or not good feedback is provided and received, is affected by a combination of different factors. Examples are the knowledge on the installed base, the quality of communication and the knowledge and skills of individual developers. It would be valuable to investigate which are the best means to help improve on these factors and to guarantee that the available knowledge of different stakeholders is used in the development project. Investigating the usefulness and effect of the support that is proposed in this research, discussed in Chapter 6, could be part of such a study.

Integration of knowledge from other research areas

This research shows that both in the literature and in practice a lot of knowledge is available about maintenance aspects. In the research, the focus has been on the knowledge that is available in the literature and from professionals that take the product development perspective as a starting point. To further develop the understanding of maintenance aspects, it would be valuable to integrate knowledge from other areas and to take other perspectives. Below, I discuss two of such perspectives.

Firstly, especially the topics of Research Questions 1 and 2 can be investigated from the perspective of the users. They are the stakeholders that have profound knowledge about the aspects that affect whether or not a good maintenance performance can be achieved. It would be most interesting to investigate which choices the customer makes when acquiring new equipment and/or services and the reasons behind the choices. This can contribute to the development of an understanding about which aspects are most relevant to address in which situations. An example of research that addresses the role of maintenance aspects in acquisition projects is the research conducted by Parada Puig (2015). His research does not focus on industrial equipment, but on passenger trains. It provides a good starting point for setting up similar research for industrial equipment.

Secondly, knowledge from the area of production development can be valuable to integrate. This field especially provides insights into how during the use life cycle phase of industrial equipment the performance can be improved and which methods and tools can help to do that. I refer to Bellgran & Säfssten (2010, Chapter 11) for an overview of the topics related to maintenance that are addressed in this research field. Closely related is the literature that explicitly focuses on developing and improving maintenance strategies for production systems, see for example Pintelon & Van Puyvelde (2006). Integration of the knowledge from these fields into product development is very valuable when it concerns the development of integrated solutions of equipment and services. The approaches and methods used in production development can be used to design and improve the maintenance services.

Bibliography

- Alsayouf, I. (2007). The role of maintenance in improving companies' productivity and profitability. *International journal of production economics*, Vol. 105, pp. 70-78.
- Andreasen, M.M., Hansen, C.T., & Cash, P. (2015). *Conceptual design. Interpretations, mindset and models*. Springer.
- Antioco, M., Moenaert, R.K., Feinberg, R.A., & Wetzels, M.G.M. (2008). Integrating service and design: the influences of organizational and communication factors on relative product and service characteristics. *Journal of the Academy of Marketing Science*, Vol. 36, pp. 501-521.
- Aurich, J.C., Fuchs, C., & Wagenknecht, C. (2006). Life cycle oriented design of technical product-service systems. *Journal of Cleaner Production*, Vol. 14, pp. 1480-1494.
- Baines, T., Lightfoot, H., Benedettini, O., & Kay, J.M. (2009). The servitization of manufacturing: a review of literature and reflection on future challenges. *Journal of manufacturing technology management*, Vol. 20, No. 5, pp. 547-567.
- Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., . . . Wilson, H. (2007). State-of-the-art in product-service systems. *Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture*, Vol. 221, No. 10, pp. 1543-1552.
- Bellgran, M., & Säfsen, K. (2010). *Production development. Design and operations of production systems*. Springer.
- Blanchard, B.S., & Fabrycky, W. J. (2014). *Systems engineering and analysis*. Pearson.
- Blessing, L.T.M., & Chakrabarti, A. (2009). *DRM, a design research methodology*. Springer.
- Boothroyd, G., Dewhurst, P., & Knight, W.A. (2011). *Product design for manufacture and assembly*. CRC Press.
- CEN, (European Committee for Standardization). (2010). European Standard EN 13306:2010 *Maintenance - Maintenance terminology*.
- Chiu, M.-C., & Okudan Kremer, G.E. (2011). Investigation of the applicability of design for x tools during design concept evolution: a literature review. *International journal of product development*, Vol. 13, No. 2, pp. 132-167.
- Cohen, M.A., Agrawal, N., & Agrawal, V. (2006). Winning in the aftermarket. *Harvard business review*, pp. 129-138.
- Coulibaly, A., Houssin, R., & Mutel, B. (2008). Maintainability and safety indicators at design stage for mechanical products. *Computers in industry*, Vol. 59, pp. 438-449.
- Dhillon, B.S. (1999). *Engineering maintainability: How to design for reliability and easy maintenance*. Gulf Professional Publishing.

- Foote, A.J. (2013). Effective R&M activities. *Proceedings of the Annual reliability and maintainability symposium (RAMS)*, Orlando, pp. 1-6.
- Gardner, S.C., & Sheldon, D.F. (1995). Maintainability as an issue for design. *Journal of engineering design*, Vol. 6, No. 2, pp. 75-89.
- Goffin, K. (2000). Design for supportability: an essential component of new product development. *Research-Technology Management*, Vol. 43, No. 2, pp. 40-47.
- Goffin, K., & New, C. (2001). Customer support and new product development. An exploratory study. *International journal of operations & production management*, Vol. 21, No. 3, pp. 275-301.
- Harrison, A. (2006). Design for service: harmonising product design with a service strategy. *ASME Turbo Expo 2006: Power for Land, Sea, and Air (Barcelona, Spain)*, pp. 135-143.
- Holman, R., Kaas, H.-W., & Keeling, D. (2003). The future of product development. *The McKinsey Quarterly*, No. 3, pp. 28-39.
- Hubka, V., & Eder, W.E. (1984). *Theory of technical systems. A total concept theory for engineering design*. Springer-Verlag.
- Imrhan, S.N. (1992). Equipment design for maintenance: Part I-guidelines for the practitioner. *International journal of industrial ergonomics*, No. 4, pp. 35-43.
- ISO, (International Organization for Standardization). (2008). International Standard ISO/IEC 15288:2008. *Systems and software engineering — System life cycle processes*.
- ISO, (International Organization for Standardization). (2011). International Standard ISO 25010:2011 *Systems and software engineering - Systems and software Quality Requirements and Evaluation (SQuaRE) - System and software quality models*.
- Jauregui Becker, J.M., & Wits, W. W. (2013). A template for design for excellence (dfx) methods. *Proceedings of the 23rd CIRP Design Conference*, Bochum, Germany, pp. 33-42.
- Jones, J.V. (2007). *Supportability engineering handbook. Implementation, measurement and management* (3rd revised ed.). McGraw-Hill.
- Knezevic, J. (1997). *Systems maintainability; analysis, engineering and management*. Chapman & Hall.
- Krishnan, V., & Ulrich, K.T. (2001). Product development: a review of the literature. *Management science*, Vol. 47, No. 1, pp. 1-21.
- Lidwell, W., Holden, K., & Butler, J. (2010). *Universal principles of design: 125 ways to enhance usability, influence perception, increase appeal, make better design decisions, and teach through design*. Beverly, Massachusetts: Rockport Pub.
- Markeset, T., & Kumar, U. (2003a). Design and development of product support and maintenance concepts for industrial systems. *Journal of quality in maintenance engineering*, Vol. 9, No. 4, pp. 376-392.

- Markeset, T., & Kumar, U. (2003b). Integration of RAMS and risk analysis in product design and development work processes. A case study. *Journal of quality in maintenance engineering*, Vol. 9, No. 4, pp. 393-410.
- Maussang, N., Zwolinski, P., & Brissaud, D. (2009). Product-service system design methodology: from the PSS architecture design to the products specifications. *Journal of engineering design*, Vol. 20, No. 4, pp. 349-366.
- Meier, H., Roy, R., & Seliger, G. (2010). Industrial Product-Service Systems-IPSS. *Cirp Annals-Manufacturing Technology*, Vol. 59, No. 2, pp. 607-627.
- Mital, A., Desai, A., Subramanian, A., & Mital, A. (2006). *Product development. A structured approach to consumer product development, design and manufacture*. Elsevier.
- Moubray, J. (1997). *Reliability-centred maintenance*. Industrial Press Inc.
- Mulder, W., Basten, R.J.I., Jauregui Becker, J.M., Blok, J., Hoekstra, S., & Kokkeler, F.G.M. (2014). Supporting industrial equipment development through a set of design-for-maintenance guidelines. *Proceedings of the International Design Conference - DESIGN 2014*, Dubrovnik, Croatia.
- Mulder, W., Blok, J., Hoekstra, S., & Kokkeler, F.G.M. (2012). *Design for maintenance. Guidelines to enhance maintainability, reliability and supportability of industrial products*. Enschede: University of Twente.
- Neely, A. (2011). The servitization of manufacturing: further evidence *18th European Operations Management Association Conference (EurOMA)*. Cambridge (UK).
- NVDO, (Nederlandse Vereniging voor Doelmatig Onderhoud). (2014). *NVDO Onderhoudskompas. Visie, trends en ontwikkelingen in de Nederlandse onderhoudsmarkt*. Amsterdam: Industrielinqs pers en platform.
- Oliva, R., & Kallenberg, R. (2003). Managing the transitions from products to services. *International journal of service industry management*, Vol. 14, No. 2, pp. 160-172.
- Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering design. A systematic approach* (Wallace, K & Blessing, L. Eds. 3 ed.). Springer-Verlag.
- Parada Puig, J.E. (2015). *Serviceability of passenger trains during acquisition projects*. (PhD Thesis), University of Twente, Enschede.
- Patton, M.Q. (2002). *Qualitative research and evaluation methods* (3rd ed.). Thousands Oaks, CA: Sage Publications.
- Pintelon, L. , & Van Puyvelde, F. (2006). *Maintenance decision making*. Leuven, Belgium: Uitgeverij Acco.
- Rapaccini, M., Saccani, N., Pezzotta, G., Burger, T., & Ganz, W. (2013). Service development in product-service systems: a maturity model. *The service industries journal*, Vol. 33, No. 3-4, pp. 300-319.

- Reymen, I.M.M.J., Hammer, D.K., Kroes, P.A., Van Aken, J.E., Dorst, C.H., Bax, M.F.T., & Basten, T. (2006). A domain-independent descriptive design model and its application to structured reflection on design processes. *Research in Engineering Design*, Vol. 16, pp. 147-173.
- Roy, R., Erkoyuncu, J. A., & Shaw, A. (2013). The future of maintenance for industrial product-service systems. *Proceedings of the 5th CIRP International Conference on Industrial Product-Service Systems*, Bochum, Germany, pp. 1-15.
- Sakao, T., Berggren, C., Björkman, M., Kowalkowski, C., Lindahl, M., Olhager, J., . . . Witell, L. (2011). Research on services in the manufacturing industry based on a holistic viewpoint and interdisciplinary approach. *Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems, Braunschweig, Germany*, pp. 27-32.
- Schotborgh, W. O., McMahon, C., & Van Houten, F.J.A.M. (2012). A knowledge acquisition method to model parametric engineering design processes. *International journal computer aided engineering and technology*, Vol. 4, No. 4, pp. 373-391.
- Smets, L.P.M., Van Houtum, G.-J., & Langerak, F. (2012). Design for availability: a holistic approach to create value for manufacturers and customers of capital goods. *Journal of Systems Science and Systems Engineering*, Vol. 21, No. 4, pp. 403-421.
- Smit, K. (2014). *Maintenance engineering and management*. Delft, The Netherlands: Delft Academic Press.
- Takata, S., Kimura, F., Van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D., & Lee, J. (2004). Maintenance: changing role in life cycle management. *CIRP Annals - Manufacturing Technology*, Vol. 53, No. 2, pp. 643-655.
- Tan, A.R. (2010). *Service-oriented product development strategies*. (PhD thesis), Technical University of Denmark (DTU).
- Tan, A.R., Matzen, D., McAloone, T.C., & Evans, S. (2010). Strategies for designing and developing services for manufacturing firms. *CIRP Journal of manufacturing science and technology*, Vol. 3, pp. 90-97.
- Thales, (CSS ILS Competence Center). (2013). Support maintenance by design. A set of design rules to consider different design possibilities to increase the availability of the system during its life cycle. (confidential).
- Thompson, G. (1999). *Improving maintainability and reliability through design*. Professional Engineering Publishing Ltd.
- Tinga, T. (2013). *Principles of loads and failure mechanisms. Applications in maintenance, reliability and design*. Springer.
- Uлага, W., & Reinartz, W.J. (2011). Hybrid offerings: how manufacturing firms combine goods and services successfully. *Journal of Marketing*, Vol. 75, pp. 5-23.
- Ulrich, K.T., & Eppinger, S.D. (2012). *Product design and development* (5 ed.). McGraw-Hill.

- Van Aken, J.E., & Romme, G. (2009). Reinventing the future: adding design science to the repertoire of organization and management studies. *Organization Management Journal*, Vol. 6, No. 1, pp. 5-12.
- Vandermerwe, S. (2000). How increasing value to customers improves business results. *Sloan management review (fall 2000)*.
- Vasanth, G.V.A., Komoto, H., Hussain, R., Roy, R., Tomiyama, T., Evans, S., . . . Williams, S. (2013). A manufacturing framework for capability-based product-service systems design. *Journal of remanufacturing*, Vol. 3, No. 8.
- Vasanth, G.V.A., Roy, R., Lelah, A., & Brissaud, D. (2012). A review of product-service systems design methodologies. *Journal of engineering design*, Vol. 23, No. 9, pp. 635-659.
- Verschuren, P., & Doorewaard, H. (2010). *Designing a research project* (2 ed.). The Hague: Eleven International Publishing.
- Wani, M.F., & Gahndhi, O.P. (1999). Development of maintainability index for mechanical systems. *Reliability engineering and systems safety*, Vol. 65, pp. 259-270.
- Wieringa, R.J. (2014). *Design science methodology*. Springer.
- Woodson, W.E., Tillman, B., & Tillman, P. (1994). *Human factors design handbook: information and guidelines for the design of systems, facilities, equipment, and products for human use*. New York: McGraw-Hill.

Appendices

Appendix I - Reliability, maintainability and supportability in the systems engineering process

This appendix contains an overview of how addressing reliability, maintainability and supportability is prescribed in the system engineering process according to Blanchard and Fabrycky (2014)¹. This is described in Section 2.1.

¹Blanchard, B.S., & Fabrycky, W. J. (2014). Systems engineering and analysis. Pearson.

Figure A.I.1: Overview of how addressing reliability, maintainability and supportability is prescribed in the systems engineering process (based on Blanchard & Fabrycky, 2014, pp. 423, 496, 595)

Appendix 2 - Interview guide used in the empirical study

This appendix contains the interview questions that are used to guide the interviews that are hold as part of the empirical study. This is discussed in Section 3.1. Both the Dutch interview questions that are used during the interviews and the English translation are added.

INTRODUCTIE OP HET INTERVIEW

Dit interview bestaat uit vier delen. Het eerste gedeelte bestaat uit een paar achtergrondvragen over het bedrijf en het productiesysteem. Het tweede gedeelte gaat over het onderhoud dat plaatsvindt aan het productiesysteem en de invloed daarvan op de prestaties. Vervolgens zullen in het derde gedeelte een aantal vragen gesteld worden over de invloed van het ontwerp van de installatie op het uit te voeren onderhoud. Ten slotte zal in het vierde gedeelte aan bod komen hoe hier tijdens het ontwerpen van de installaties rekening mee wordt gehouden.

Ik zal het interview opnemen met deze audio recorder. De opnames wil ik gebruiken voor het uitwerken van het interview. Gaat u hiermee akkoord? Daarnaast zal ik aantekeningen maken om de lijn van het gesprek in de gaten te houden. Het gehele interview zal ongeveer één à anderhalf uur duren.

Hebt u hierover nog vragen?

INTERVIEWVragen

DEEL 1 - ACHTERGROND GEINTERVIEWDE

Tijdsindicatie: ± 5 min

1. Wilt u zichzelf kort voorstellen?
 - Naam:
 - Functie:
 - Type persoon in de context van het interview:
 - i. Ontwikkelaar/ontwerper installaties
 - ii. Ontwikkelaar/ontwerper service
2. Kunt u kort iets vertellen over het bedrijf?
 - Hoofdactiviteit:
3. Kunt u kort iets vertellen over het productiesysteem waarin de installaties worden gebruikt?
 - Installaties typerend voor het productiesysteem

DEEL 2 – ONDERHOUD PRODUCTIESYSTEEM

Tijdsindicatie: ± 15 min

4. Wat zijn de noodzakelijke onderhoudswerkzaamheden aan het productiesysteem?
5. Hoe ziet het onderhoudsprogramma er uit voor ... (installaties in het productiesysteem)?
 - Dagelijks onderhoud:
 - Wekelijks/maandelijks onderhoud:
 - Jaarlijks onderhoud:
 - Korte stops:
 - Grote stops:
 - Revisies:
6. Wat zijn de belangrijkste oorzaken voor ongepland onderhoud?
 - Vb. onverwachte slijtage, extreme omstandigheden, verkeerd gebruik installaties, onverwachte slijtage, gekozen onderhoudsstrategie
7. Welke prestatie indicatoren gebruiken jullie om de prestaties op het gebied van onderhoud te meten?
8. Waardoor worden deze prestatie indicatoren (genoemd in vraag 7) beïnvloedt?
 - Vb. Beschikbaarheid en kosten van reserveonderdelen, personeel, gereedschappen, faciliteiten/werkplaatsen
9. Wat zijn de belangrijkste prestatie indicatoren voor het productiesysteem (waarin de installaties worden gebruikt)?
10. Wat is de invloed van onderhoud op deze prestatie indicatoren (genoemd in vraag 9)?
 - Invloed op beschikbare productie tijd
 - Invloed op productiekosten
11. Hoe verhouden de onderhoudskosten zich tot de totale levenscycluskosten van het productiesysteem?
 - Hoe verhouden de onderhoudskosten zich tot de initiële investeringen?
 - Hoe verhouden de onderhoudskosten zich tot de operationele kosten?
12. In hoeverre is het belangrijk dat onderhoud wordt meegenomen bij het ontwikkelen van het productiesysteem?

DEEL 3 – INSTALLATIE ONTWERP EN ONDERHOUD

Tijdsindicatie: ± 15 min

Vragen met betrekking op een type installatie dat typerend is voor het productiesysteem

13. Hoe wordt deze installatie onderhouden?
 - Welke onderhoudstaken zijn er?
 - Door wie wordt het onderhoud uitgevoerd?
 - Waar wordt het onderhoud uitgevoerd?
 - Welke gereedschappen zijn er nodig?
 - Worden er reserveonderdelen op voorraad gehouden?
14. Kunt u voorbeelden noemen van aspecten van het ontwerp waarbij GOED rekening is gehouden met het uit te voeren onderhoud?
15. Kunt u voorbeelden noemen van aspecten van het ontwerp waarbij NIET GOED rekening is gehouden met het uit te voeren onderhoud?
16. Welke onderdelen van de onderhoudsorganisatie zijn speciaal aangepast op deze installatie, en welke waren er al?
17. Waarom kiezen klanten voor deze specifieke installaties?
 - Maken de klanten afwegingen met betrekking tot onderhoud bij de keuze van installaties? Zo ja, welke?
 - Welke andere type installaties overwegen klanten aan te schaffen?

DEEL 4 - ONTWERPEN VOOR ONDERHOUD

Tijdsindicatie: ± 20 min

Vragen met betrekking op een type installatie dat typerend is voor het productiesysteem

18. Wordt onderhoud meegenomen bij het ontwikkelen van de installaties?
19. Wanneer in het ontwikkeltraject speelt onderhoud een rol?
20. Heeft de onderhoudsorganisatie kennis die nuttig is voor de ontwerpers van de installaties?
 - a. Wie heeft het?
 - b. Welke (soort) kennis is het?
21. Wordt er kennis teruggekoppeld vanuit over onderhoud naar de ontwikkelaars van de installaties?
 - Door wie?
 - Naar wie?
 - Welke kennis (zowel expliciete als impliciete kennis)?
22. Is er een formeel mechanisme om voor het terugkoppelen van deze kennis?
23. Zijn er aanpassingen gedaan aan het ontwerp van de installaties die het uit te voeren onderhoud beïnvloeden op basis van onderhoud?
24. Welke ontwerpmethoden en –gereedschappen worden gebruikt tijdens het ontwikkeltraject?
 - Vb. Richtlijnen, checklijsten, analyses (FMECA, FTA, MTA,...)

EINDE INTERVIEW

25. Hebt u nog andere opmerkingen of zaken die u kwijt wilt naar aanleiding van de onderwerpen die in dit interview aan de orde zijn gekomen?

Hartelijk bedankt voor uw medewerking aan dit interview. Zou ik eventueel nog een keer telefonisch of via de e-mail contact op kunnen nemen voor een aantal vervolgvragen?

Als u nog vragen of opmerkingen heeft naar aanleiding van dit interview, of wanneer u later nog dingen te binnen schieten, kunt u altijd contact met mij opnemen.

INTRODUCTION TO THE INTERVIEW

The interview consists of four parts. The first part consists of a number of background question about the company and the production system. The second part covers the maintenance that is performed on the production system and the influence of maintenance on the performance of the production system. Then, in the third part a number of questions are asked about the influence that the design of the equipment has on the maintenance that is performed. Finally, in the fourth part, I will ask about how maintenance is addressed during the development of the equipment.

I will record the interview with this audio recorder. I will use the recordings for the analysis of the interview. Do you agree with this? Also, I will make notes to keep an eye on the line of conversation. The whole interview takes about one and an half hour.

Do you have any questions?

INTERVIEW QUESTIONS

PART 1 – BACKGROUND INTERVIEWEE

Time indication: ± 5 minutes

- I. Could you introduce yourself?
 - Name:
 - Function:
 - Type of person in the context of the interview:
 - i. Developer/designer equipment
 - ii. Developer/designer maintenance service
2. Can you briefly introduce the company?
 - Main activity:
3. Can you briefly introduce the production system in which the equipment is used?
 - Typical equipment that is used in the production system:

PART 2 – MAINTENANCE ON THE PRODUCTION SYSTEM

Time indication: ± 15 minutes

4. What are the necessary maintenance activities for the production system?
5. How does the maintenance programme look like for ... (equipment within production system)?
 - Daily maintenance:
 - Weekly/monthly maintenance:
 - Yearly maintenance:
 - Short stops:
 - Large stops:
 - Overhauls:
6. What are the main reasons for unplanned maintenance?
 - Examples: unexpected wear, extreme circumstances, improper use of the equipment, chosen maintenance strategy.
7. What performance indicators are used to measure the performance of maintenance?
8. What does influence the levels of performance on these indicators (mentioned in question 7)?
 - Examples: availability and costs of spare parts, personnel, tools, facilities/workshops.
9. What are the most important performance indicators for the production system (in which the equipment is used)?
10. What is the influence of maintenance on these performance indicators (mentioned in question 9)?
 - Influence on available production time
 - Influence on production costs

11. What proportion do the maintenance costs bear to the total life cycle cost of the production system?
 - What proportion do the maintenance costs bear to the initial investment?
 - What proportion do the maintenance costs bear to the operational expenditures?
12. To what extent is it important that maintenance is addressed during the development of the production system?

PART 3 – EQUIPMENT DESIGN AND MAINTENANCE

Time indication: ± 15 minutes

Questions regarding a particular type of equipment within the production system.

13. How is the equipment maintained?
 - What maintenance activities are performed?
 - Who does perform the maintenance?
 - Where is the maintenance performed?
 - What tools are required to perform the maintenance activities?
 - Are any spare parts kept on stock?
14. Can you give examples of the equipment design in which in which maintenance aspects are well addressed?
15. Can you give examples of the equipment design in which maintenance aspects are not sufficiently addressed?
16. What elements of the maintenance service are specially adapted to the equipment, and elements did already exist?
17. Why do customers select this equipment?
 - Do the customers consider maintenance aspects when they acquire new equipment? If yes, which?
 - What other types of equipment do customer consider to acquire?

PART 4 - MAINTENANCE IN THE DEVELOPMENT PROCESS

Time indication: ± 20 minutes

Questions regarding a particular type of equipment within the production system

18. Is maintenance addressed during the development of the equipment?
19. When in the development process does maintenance play a role?
20. Does the service/maintenance department has particular knowledge that is useful for developers of the equipment?
 - a. Who does have it?
 - b. What (type of) knowledge?
21. Is there any feedback about maintenance given to the developers of the equipment?
 - By who?
 - To whom?
 - What knowledge (both explicit and implicit knowledge)?
22. Do the company use a formal mechanism for the provision of feedback?
23. Are any changes made to the design of the equipment that influence the maintenance activities to be performed?
24. What design methods and tool are used in the development process?
 - Examples: guidelines, checklist, analyses (FMEA, FTA, MTA, ...)

END OF THE INTERVIEW

25. Do you have other remarks of things that you would like to share related to the topics addressed in this interview?

Thank you very much for your participation in this interview. Could I possibly contact you again by phone or email for some follow-up questions?

If you have any question or comments regarding to this interview or if any new thoughts come up, please feel free to contact me.

Appendix 3 - Examples of parts of the in-depth interviews

This appendix contains examples of parts of the conversations during the in-depth interviews. This appendix is added to illustrate the depth of the interviews and the way in which different topics are discussed. The in-depth interviews are discussed in Section 3.1.2. The examples show that a broad range of topics is discussed. Also, they show that the answers that interviewees provide, contain information that is related to different topics. For example, the question of Example 1 is about the relevant maintenance aspects, while the answer also provides information that is related to the way in which they can be addressed. The question of Example 2 is about the development process. The answer also provides information about the factors that affect whether maintenance aspects are addressed successfully.

Example 1

[Interviewer] Ok, I would like to talk a bit about the design of the equipment and why it makes the equipment easy to maintain. You already said that modularity is an important aspect. [Interviewee] Design of the equipment is done by the project groups and there are good and bad examples. That's a pity, because everyone should do it in the right way. That is also the reason that we talk about the lessons that we have learnt in the past about things that should not be done anymore. But okay, I already said that modularity is important. Also, we use initialization functionalities with which can be checked whether the system functions correctly. That is very powerful, also for maintenance. Also, we monitor the performance of a particular part and use the gathered information to prepare the spare part in time. Furthermore, you need to look at the spare that you need and at the accessibility and repairability, how quick can something be accessed. It is not desired that you need a ladder to reach something. And is it possible to use standard tools to exchange something? Standard tools means a standard screw drive or hex key. Within the tool that we use, which you already have seen, also such things are mentioned. For each spare part, an estimation is made of the probability that it fails and the time that it takes to access it, to replace it and the time for the recovery.

Example 2

[Interviewer] When do you address maintenance aspects during the development of the equipment? Is that already from the start of a development project? [Interviewee] You could see it as follows. Within our company we have a particular process that we follow when we start developing a particular product. You could roughly divide the process into four parts. The first part concerns the definition of the requirements specifications, in the second part we prepare all kind of service documentation and other things. Then we have a phase during which we test whether or not the specifications are met. We try to do this at our company. However, the extent to which that is possible depends on the time pressure that we have. Finally, the system goes to the customer. Then, what often happens is that we have some time pressure and that issues have to be solved at the customers' site to fulfill the specifications. So that's another type of work. You could imagine that, dependent on the stage of the project that you are in, the stage that you are in differs for different products, because they are all in a different development stage, that you have different types of work.

Appendix 4 - Illustrations of the prepared mind maps

This appendix contains illustrations of the mind maps that are constructed as part of the analysis of the data that is retrieved via the in-depth interviews. Figure A4.1 depicts an illustration of the structure of the mind maps. Figures A4.2 depicts an example of one of the real mind maps that is made to illustrate the amount of data that is retrieved. It is made unreadable on purpose because it contains company specific information. The analysis of the data that is retrieved via the in-depth interviews is discussed in Section 3.1.2.

Figure A4.1: Illustration of the structure of a mind map used for data analysis

Figure A4.2: Mind map of an in-depth interview

Appendix 5 - Information retrieval questions used in the empirical study

This appendix contains the overview of the questions that is used to distill the useful information from the data that was retrieved via the in-depth interviews. This is discussed in Section 3.1.

Business activities

1. What is the role of maintenance in the business activities of the company and in the offerings to its customers?
 - a. What is the business strategy of the company?
 - b. What equipment and services does the company offer?
 - c. What do (potential) customers expect from the equipment and services that the company offers?

Equipment life cycle performance

2. What is the role of maintenance in good performance of the equipment during its use and support life cycle phases?
 - a. What defines good performance of the equipment during its use life cycle phase?
 - b. How does maintenance contribute to or hinder good performance of the equipment during its use life cycle phase? / How can good maintenance performance be defined?

Relevant maintenance aspects

3. What maintenance aspects are addressed during the development of the equipment and its maintenance service? And what approaches are followed when doing that?
 - a. What are the characteristics of the maintenance plan of the equipment?
 - b. What design aspects of the equipment influence the need for and the performance of maintenance?
 - c. What aspects, other than the design aspects of the equipment, influence the need for and the performance of maintenance?
 - d. What approaches are followed when addressing maintenance aspects in a development project? And why are these approaches followed?

Development process

4. How are maintenance aspects addressed in a development project and what does make the used approaches successful or not?
 - a. What maintenance development activities are undertaken in a development project? Why are they undertaken?
 - b. What activities are undertaken to influence decisions on maintenance aspects in a development project? And why are they undertaken?
 - c. What activities/methods/tools are used to address maintenance aspects in the development project?
 - d. How can the success of a development project be defined?
 - e. What actors and factors do contribute to or hinder successfully addressing maintenance aspects in a development project?

Appendix 6 - Initial findings

This appendix contains the initial findings of the empirical study. This is discussed in Section 3.1. Figure A6.1 depicts the initial model of relevant maintenance aspects. Tables A6.1 and A6.2, respectively, represent the initial overview of activities that developers perform to address maintenance aspects and the initial overview of factors that affect whether addressing the maintenance aspects is successfully done. The model and the two overviews are supplied to the employees who participated in the validation sessions. With respect to the overview of factors and activities, also descriptions on how they applied to the individual companies were added. These descriptions are not added to this appendix because of confidentiality reasons.

Figure A6.1: Initial model of relevant maintenance aspects

Development activity	Description
1. Defining and specifying requirements	<p>In the program of requirements, specific requirements for maintenance aspects are defined. These are usually defined at the start of a project, and are, if required, adjusted based on new ideas or insights during the project.</p> <p>Requirements related to maintenance are, for example, life time of components, minimum time span between maintenance actions, time required for maintenance actions, or budgets for the total required maintenance time and costs.</p>
2. Everyday discussions	<p>In development projects, several people, with similar and different specializations, work together. They meet regularly, both in formal meetings and informally, and discuss the various topics in the development project, including the maintenance aspects.</p>
3. Design reviews	<p>By means of design reviews, the design of the product/service offering being developed is evaluated to verify the outcomes of the previous design activities and to identify the necessary improvements that need to be made. Design reviews take place in different design and development stages and can be used as milestones when the project has sufficiently progressed to continue to the following stage.</p> <p>With respect to maintenance, important aspects that are reviewed are the frequency of the required maintenance activities, the ease of and time required to perform them, and the quality of the service deliverables. Reviewing these aspects is guided by a combination of the defined requirement specifications, the experience of the equipment and maintenance developers, and the experience of service engineers.</p>
4. Quantitative analyses to analyze wear and failure behavior and life time	<p>Quantitative analyses, by means of calculation models and simulation models, are used to get an understanding of the failure mechanisms of the system and the wear behavior of the components. A good understanding is required to be able to make the right design choices and changes influencing the wear and failure behavior, and to be able to apply condition-based or predictive maintenance.</p>
5. Testing activities - Endurance tests of individual components - Tests of whole system performance	<p>During the development project, testing is used as a means to support design decisions. With respect to maintenance testing activities are important for prediction of the life time of individual components, and to detect possible problems already in early stages of the development project. Two main categories of testing activities are distinguished:</p> <p>(1) Testing the wear behavior of individual components to predict the life time of the specific components. Two important factors for the accurateness and usefulness of the testing results are the possibility to 'accelerate' the use and wear of the components, and the possibility to simulate the environmental and operational conditions in practice.</p> <p>(2) Testing the overall system performance. These types of test are performed to test the functional performance of the systems and to find out what possible problems and failures can occur during operation. Typically, it is not known (exactly) beforehand what aspects are tested.</p>

Table A6.1: Initial overview of development activities that developers perform to address maintenance aspects

6. Analyses for maintenance related properties - Maintenance task specific performance measures - Budget measures for total down time and costs	<p>To evaluate the performance of the product/service offering being developed, maintenance related performance measures are analyzed. Two types of measures can be distinguished:</p> <ul style="list-style-type: none"> - Specific maintenance task times, such as the mean time to diagnose and mean time to repair. - Budgets representing the total time that is required for the maintenance activities over a particular period and/or the total costs that this leads to. These are usually expressed in terms of the Total Cost of Ownership, representing the direct maintenance costs made for labor and for spare parts.
7. Maintenance service design activities	<p>In the development process, a number of maintenance development activities take place. This includes the preparation of a number of maintenance deliverables: for example, the maintenance scheme with the required maintenance actions and their planning, working instructions and maintenance manuals for the customer and the service engineers, training documents for the service organizations to train the service engineers, tools to support diagnostics of failures, and lists of required spare parts.</p> <p>Also, development activities focusing on improving the execution and management of the maintenance activities take place. Two examples of such activities are the development of remote support for service engineers and development of maintenance management software tools.</p>
8. Improvements during development/pilot-run phase	<p>In the development/pilot-run stage of the development process, the equipment is installed in the field for the first time. This stage is needed to get an understanding of the functioning of the system in real environmental and operational conditions. Developments that are made in this stage concern design improvements and improvements on the maintenance scheme.</p> <p>The development activities focus on, firstly, achieving a system that functions 'stable' in the particular customer environment, and, secondly, on achieving a system that meets its productivity specifications. At the moment that the system functions according to its requirement specifications, the system is considered to be mature, so its development stage ends.</p>
9. Developing upgrades/improvements during life time	<p>During the life time of the equipment, improvements on the equipment and its maintenance service are developed.</p> <p>Firstly, analyses on the performance of the system, its wear and failure behavior and the required maintenance activities are made. These analyses are used to optimize the maintenance scheme in such a way that a good balance is found between the system's technological performance, productivity and the costs made for the maintenance activities.</p> <p>Depending on the contract between the equipment manufacturer and its customer, this is the responsibility of, and performed by, either one of them.</p> <p>Secondly, upgrades or commercial options are developed to solve design flaws and/or to improve the system's performance. A number of these are related to improve the system's maintenance related performance measures.</p>

Table A6.I continued

10. Feedback gathering and analysis	<p>Feedback from the field is a source of information used to learn about the performance of the system in the field. It provides knowledge about, for example, the reasons why the system fails or performs better or worse than expected, why more or less maintenance is required than expected, and why maintenance activities are easy or difficult to perform.</p> <p>Feedback is retrieved in different ways:</p> <ul style="list-style-type: none"> (1) Developers get feedback when they are working on the machines in the field themselves. (2) Service engineers, sales employees, or others who work in the field or have contact with the customer or user regularly, share their feedback pro-actively. (3) Feedback systems are used to report the problems that have occurred and the maintenance activities that are performed, for example, forms are filled out or notes are made. (4) Meetings are held regularly with people from development departments and people that work in the field to discuss issues that are noticed in the field.
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Table A6.1 continued

Factor	Description
1. Knowledge on maintenance aspects in equipment development projects (both for the individual developers and the development teams) - Knowledge on the influence of the interrelations equipment design/maintenance service design/service environment on the maintenance performance aspects - Knowledge on the influence of the interrelations equipment design/environmental conditions/operational conditions on the maintenance performance aspects	<p>The basis for making good decisions is having good knowledge on the topic of interest. Knowledge that is particularly relevant with respect to the maintenance aspects can be categorized into two themes:</p> <ul style="list-style-type: none"> - Knowledge on the influence of the interrelations -equipment design/maintenance service design/service environment - on the maintenance performance aspects. For example, knowledge on how the equipment and maintenance diagnostic tools can be designed in such a way that under all circumstances, a service engineer in the field, in all circumstances, can easily diagnose a failure and does not need the help of second or third line service engineers. - Knowledge on the influence of the interrelations -equipment design/environmental conditions/operational conditions- on the maintenance performance aspects. For example, wear and failure behavior of the equipment is often different for specific customers and/or locations. A good understanding of the influence of these is required to develop an effective and efficient maintenance scheme. For successful application of predictive maintenance strategies, a good understanding of these relations is a prerequisite.
2. Availability and quality of data about: - Equipment wear and failure behavior in relation with environmental conditions and/or operational conditions	<p>During the life time of the equipment, data can be gathered about the wear and failure behavior, the maintenance activities that are performed, and the system's technological and productivity performance. This data can be used to quantitatively analyze how the maintenance scheme and/or the equipment design can be improved. If a large installed base of a particular system is used in the field, statistics can be used to analyze system wear behavior and performance. These analyses can help to get insight into the variation of the system performance at various customers and the reasons behind that. Important for the use of the data is that it is provided to the equipment or maintenance developers in an easily usable format, so that little processing of the data is required.</p>
3. Feedback on: - Possibilities to improve equipment design and maintenance design with respect to maintenance execution - Possibilities to improve equipment design and maintenance design with respect to equipment wear and failure behavior in particular environmental conditions and/or operational conditions	<p>Feedback from the field is an important source of information as starting point for design improvements. The feedback that is desired by the equipment developers is feedback about issues that can only be learnt from the field. Feedback about two types of issues is especially relevant:</p> <ul style="list-style-type: none"> - Feedback related to the ease of performing maintenance activities. Service engineers who carry out the maintenance activities can provide valuable input about why certain maintenance tasks are easy or difficult to perform. - Wear and failure behavior due to specific environmental and/or operational conditions. There are various reasons why a system can fail; for example, human errors, design flaws, and a too high load of the equipment. The reasons behind these failures give insights into what design improvements could be made to improve the performance of the equipment.

Table A6.2: Initial overview of development activities that developers perform to address maintenance aspects

<p>4. Performance indicators and requirements specification on:</p> <ul style="list-style-type: none"> - Content/definition <ul style="list-style-type: none"> - Representativeness for customer demands and wishes - Representativeness for properties relevant for the company's business - Use <ul style="list-style-type: none"> - Relative importance of performance indicators and requirements when making design decisions 	<p>Performance indicators and requirement specifications are defined to direct development activities to achieve a system with a certain performance. The product/service offering being developed should have properties that are relevant for a company's business and that are appealing for the (potential) customers.</p> <p>Besides a good definition of the performance indicators and requirement specifications, the use of these in the development process is an important factor that determines whether the developed system meet the set specifications or not. Especially, the relative importance that is given to the maintenance related performance indicators determine how much effort is made to meet the defined requirement specification at the end of the development project.</p>
<p>5. Quality of communication</p>	<p>Good communication between people in development projects is essential for making optimal use of each other's expertise. Communication takes place both informally, during everyday discussions, and formally, in design reviews and project meetings. It is desired that in all stages of the development project people understand each other and can provide input that is useful for the other developers in the project. The quality of communication seems to be better when something tangible can be discussed, such as a 3D-model, a drawing, or a prototype, and/or specific performance aspects.</p>
<p>6. Individual quality and skills developers</p>	<p>Individual quality and skills of the equipment and maintenance service developers, such as their creativeness, knowledge and experience, is generally considered as the basis for successfully developing products and services. Courses and training on the topic of maintenance aspects help to enhance the quality and skills of the developers. Also, visits to the customer sites and temporarily assisting the service engineers in the field helps to give the developers the required knowledge to successfully take into account the maintenance aspects.</p>
<p>7. Methods/tools to support development decisions specifically for maintenance aspects</p> <ul style="list-style-type: none"> - Relevance - Usability 	<p>To support decision making during the development of the complex equipment and maintenance services, companies develop their own methods and tools. Methods and tools that are developed to address maintenance aspects, focus on:</p> <ul style="list-style-type: none"> - Explicitly indicating the required preventive and expected corrective maintenance actions. - Explicitly calculating the consequences of the maintenance actions with respect to time required, costs for labor, costs for spare. - Enabling good communication about maintenance aspects.

Table A6.2 continued

8. Company organizational and cultural aspects	<p>Company organizational and cultural aspects are important for the success of a development project. Related to addressing maintenance aspects, the following two points are identified:</p> <ul style="list-style-type: none"> - The organizational structure of the companies. Having special departments for, for example, new developments and improvement projects on current systems, or special departments for maintenance service developers and equipment developers, can lead to less attention for maintenance, because it is not a topic in the everyday discussions and/or feedback is only returns one of the departments. - Awareness created by the company and project management. Awareness for addressing maintenance aspects can be created by company management or project management, by giving more attention to it.
9. Launch timing	<p>Launch timing is a decision that trades off the necessity of bringing the product to the market and the completeness of the product. On the one hand, it is important to bring the product to the market as early as possible, to be earlier than competitors, to win new markets and/or not to lose current markets. On the other hand, bringing the product to the market when it is not completed yet, for example, if the maintenance requirement specifications have not been met, can have consequences during the later life cycle stages. Possible consequence could be that problems will occur and need to be solved by design changes, extra maintenance is required to compensate for design flaws, various version of the equipment are installed in the field, making the maintenance activities more complicated to perform and organize.</p>
10. Timing addressing maintenance aspects	<p>Maintenance aspects are discussed in different stages of the development projects. Especially elementary design choices, usually choices that need a lot of work when changed in a later development stage, are important to be addressed in early stages. To review a product being developed on maintenance aspects, the service departments are usually involved. However, it depends on the stage of the development project how much input can be provide by the representatives from the service department.</p>
11. Supplier involvement - Knowledge about the use, maintenance and performance of their components and technologies	<p>The developed systems consist for a large part of components and technologies that are developed by suppliers. The equipment manufacturers need the knowledge and expertise about application of these components in their systems that they have not themselves. Also, the suppliers need feedback from the equipment manufacturers about the performance of their components and technologies when they are integrated in the systems of the equipment manufacturers.</p>
12. Customer involvement - Shared understanding about desired performance	<p>Customer involvement is especially relevant for the definitions of the performance indicators and requirement specifications. Both the equipment manufacturer and the customer should have the same understanding about the performance of the product/maintenance service offering being developed. Involving the customer in the process of defining the performance indicators helps to get such a shared understanding, and direct the developers to work on aspects that are relevant to fulfill the customer's demands and wishes.</p>

Table A6.2 continued

Appendix 7 - Feedback form used in the empirical study

This appendix contains the feedback form that is used in the empirical study. The use of the feedback form is described in Section 3.2.3. Within the feedback form, I refer to “Appendices 1, 2 and 3”. These appendices were added to the feedback forms and contained the initial findings of the research. Appendix 1 was the initial model of relevant maintenance aspects (see Section 4.1). Appendix 2 was the initial overview of the development activities that developers use to address maintenance aspects (see Section 5.2.2). Appendix 3 was the initial overview of factors that affect whether addressing maintenance aspects is done successfully (see Section 5.3.2).

Feedback form – results PhD research project

1. Relevant maintenance aspects - See Appendix 1

1a. Appendix 1 contains a model of the relevant maintenance aspects that are identified. These are organized into six categories, each representing a different topic for the development of equipment/service offers.

Do the categories reflect the topics in the development projects of equipment/service offerings in your company? Why or why not?

1b. each category of the model contains a number of specific aspects.

Do you agree with the chosen aspects? Should any of the aspects be removed or added? If yes, which? And why?

(Please go through the overview and, if necessary, cross the aspects that are not relevant and add new ones)

2. Development activities and factors affecting the success of addressing maintenance aspects - See Appendix 2 and 3

2a. Appendix 2 contains an overview of the identified development activities that are used to address maintenance aspects.

Does the overview contain all the relevant approaches that are used to address maintenance aspects in your company? Should any of them be removed or added? If yes, which? And why?

(Please go through the overview and, if necessary, cross the approaches that are not relevant, add new ones)

2b. Appendix 3 contains an overview of the identified factors that contribute to, or hinder, successfully addressing maintenance aspects in development projects.

Does the overview reflect all relevant factors that contribute to, or hinder, successfully addressing maintenance aspects in your company? Should any factors be removed or added? If yes, which? And why?

(Please go through the overview and, if necessary, cross the factors that are not relevant, add new ones, and circle the most important ones)

3. Currently relevant topics in industry - See Appendix 1, 2 and 3

3a. What are, currently in your organization, the most important maintenance aspects to focus on in development projects? (See Appendix 1)

(Please go through the overview and circle the most important ones)

3b. What are, currently in your organization, the most important activities and factors to focus on to improve the success of development projects, with respect to addressing maintenance aspects? (See Appendices 2 and 3)
(Please go through the overviews and circle the most important ones)

4. Final questions

4a. Have the presented results provided you any new insight? If yes, which? If no, why not?

4b. Do you have any other comments or feedback? Please, share them here below.

Information about respondent

Name:

Function:

Department:

Thanks a lot for sharing your insights!

Appendix 8 - Answers to questions at the feedback forms

This appendix contains the answers that are given at the questions at the feedback form. The feedback forms and their use are discussed in Section 3.1. Sections 4.1.1, 5.2.1 and 5.3.1 discuss how the answers are used to improve the initial findings of the research.

Answers to Question 1a

[Answer 1] Yes, although some categories are more emphasized than others in our company.

[Answer 2] Yes.

[Answer 3] Aside from feedback already given in our session, it does match.

[Answer 4] Yes, it represents the organization/development aspects.

[Answer 5] The categories are logically chosen. However, I do not always see them back in our company. Your research provides a good guide for that. Furthermore, maintenance aspects are both addressed in new product development projects and in projects in which systems are engineered for customers. The scenario related aspects more often come back in project in which systems are engineering for the customer than in new product development projects. It should be discussed which aspects must be addressed at the product level and which at the system level.

Answers to Question 1b

[Answer 6] Aspects seem clear and complete

[Answer 7] Suggestion to add: (1) Available infrastructure (data restrictions, intellectual property information customer, etc.) to service environment, (2) spare parts and service tools inventory to maintenance resources. A remark is: Picture is the ideal world, in real life you need to balance between constraints such as budget, timing, etc. What is the advice to focus on for most optimum choice?

[Answer 8] Suggestion to add service engineer support from 3rd line.

[Answer 9] Aside from feedback already given in our session, it does match.

[Answer 10] Yes

[Answer 11] Everything what is mentioned is right. What could be added, are: (1) mentioning the safety aspects for both the equipment and the maintenance service design, (2) system redundancy, because more and more customers used the systems 365/24/7. Does the product and system design (and operation of the customer) allow to perform particular maintenance activities? For example through making particular critical functions redundant, and (3) performance aspect technical availability (which is off course directly related to the mean time to repair and mean time between failures). These should be determined per product and be validated with data from the field. In more and more service contracts, technical availability is used as key performance indicator.

[Answer 12] Agree. Some other aspects that could be considered: (1) (maintenance) costs: in the end everything is about money, if a concept can be evaluated against the total costs needed (development + maintenance = lifecycle), it easier to compare alternatives in order to find the best design, (2) use of redundancy (especially sensors), (3) use of remanufacturing, are there designs for which it is the most optimal strategy to exchange subassemblies (modules) and overhaul the old subassembly (customer himself or send it back to the OEM)? (3) Identification of parts could help to classify failures into manufacturing related causes (like a poor quality batch)

or customer related causes (which customers do have similar issues?), or identify the supplier of the parts that are used in a system.

Answers to Question 2a

[Answer 13] As far as I can tell the overview seems complete

[Answer 14] Yes

[Answer 15] Yes

[Answer 16] Everything that is mentioned, is right. My question is “how do you ensure that it will be performed?” I would implement the steps in the development process and add milestones to them. After step 8, a formal “product take-over” should take place during which the service organization accepts the product and commits to perform the maintenance against on beforehand determined costs and service levels.

[Answer 17] Suggestion to add: customer escalations, because ...

Answer 17 provides information related about maintenance aspects, which is not the topic of Question 2a of the feedback form, but is related to Question 1b. Therefore it is used as feedback for the improvement of the model of relevant maintenance aspects (see Section 4.1.1)

Answers to Question 2b

[Answer 18] Seems complete

[Answer 19] Missing financial / economical influence

[Answer 20] Suggestion to add the factor that certain maintenance service deliverables, among which the preventive maintenance scheme, are standard deliverables of the development process.

[Answer 21] I miss two aspects: (1) To be able to have a good feedback loop, you need to know exactly which system is installed at which customer (which product version, which component versions, which component suppliers, etc.), (2) availability of components in the future (which life cycle policy do suppliers use, what is the impact if a component is not available anymore, upgradeability)

Answer 20 partly provides information about relevant maintenance aspects (the part concerning the availability of components), which is not the topic of Question 2a of the feedback form, but is related to Question 1b. Therefore, the provided feedback is also used as feedback for the improvement of the model of relevant maintenance aspects (see Section 4.1.1)

Answers to Question 3a

I do not provide the answers to this questions, because they are not used as input for the construction of the research results.

Answers to Question 3b

I do not provide the answers to this questions, because they are not used as input for the construction of the research results.

Answers to Question 4a

[Answer 22] Not many new insights. Strength lies more in gathering/presenting maintenance aspects in a structured way and offering a complete overview.

[Answer 23] Not really

[Answer 24] I find that you have created a nice overview that we can use as guide during the development of products and systems.

[Answer 25] Not very new insights, provides a good total overview

[Answer 26] For me it is new to even look in a structured way at maintenance. I do recognize many aspects. I cannot think of a practical use for design engineering for now.

Answers to Question 4b

I do not provide the answers to this questions, because they are not used as input for the construction of the research results.

Appendix 9 - Additions to initial findings

This appendix presents the additions that are made to the initial findings after holding the validation sessions. This is discussed in Sections 3.1.3, 4.1.1, 5.2.1 and 5.3.1. The initial findings were initial versions of:

- The model of relevant maintenance aspects that is presented in Figure 4.1.
- The overview of development activities that developers perform to address maintenance aspects and their descriptions, which are presented in Section 5.2.2
- The overview of factors that affect whether addressing maintenance aspects can be done successfully and their descriptions, which are presented in Section 5.3.2

The following changes were made after analyzing the data that was retrieved via the validation sessions:

Relevant maintenance aspects

The following is added within the categories:

- System level performance aspects: the complete category is added.
- Item level performance aspects are defined at one more level of detail.
- Scenario aspects: cleaning regime of customers; maintenance tools inventory; available infrastructure; differences in performing maintenance; life cycle policy of suppliers; escalations by customers.
- Equipment design aspects: redundancy of systems; safety properties; remanufacturability properties; component selection.
- Scenario related equipment design aspects: Component selection ◊ life cycle policy suppliers.
- Maintenance service design aspects: safety procedures; remanufacturing organization; service engineer support; maintenance tools inventory; customized maintenance scheme.
- Equipment & Maintenance service design aspects: System, sub-system and components redundancy ◊ maintenance scheme / spare parts inventory management; remanufacturability properties ◊ maintenance scheme / remanufacturing organization; system complexity / easiness to diagnose ◊ maintenance diagnostic tools / maintenance support services.

Development activities that developers perform to address maintenance aspects

No changes are made.

Factors that affect whether maintenance aspects are successfully addressed

Two factors are added, namely: *Factor 4, Knowledge on the installed base* and *Factor 9, the extent to which addressing maintenance aspects is embedded in the development process*.

Appendix 10 - Comparison overviews of development activities

This appendix shows how the activities that are prescribed by Blanchard & Fabrycky (2014)¹ and Takata et al. (2004)² to address maintenance aspects can be related to the overview of development activities that is presented in Section 5.2.2. This is discussed in Section 5.2.3.

Blanchard & Fabrycky (2014) prescribe the activities that need to be performed to address reliability, maintainability and supportability during the systems different stages of the systems engineering process. Appendix 1 provides an overview of the activities that they prescribe. Table A10.1 shows how the prescribed activities to address reliability and maintainability can be related to the activities of the overview in Section 5.2.2. The activities that Blanchard & Fabrycky (2014) prescribe to address supportability are not included, because these focus on the design of a support system. I have not investigated this in my research. Comparing the overviews shows that all activities that are prescribed by Blanchard & Fabrycky (2014) can be related to one of the activities in the developed overview. Also, it shows that they are described at a more detailed level.

Takata et al. (2004) prescribe six activities to address maintenance, namely: maintainability design, maintenance strategy planning, maintenance task control, evaluation of maintenance results, improvement of maintenance and products, dismantling planning and execution. Table A10.2 shows how the first five of these activities can be related to the developed overview. The last activity, dismantling planning and execution, does not come back in the developed overview. Comparing the overviews shows that the activities by Takata et al. (2004) are more general and only give an general idea about the activities that need to be performed.

¹ Blanchard, B.S., & Fabrycky, W. J. (2014). Systems engineering and analysis. Pearson.

² Takata, S., Kimura, F., Van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D., & Lee, J. (2004). Maintenance: changing role in life cycle management. CIRP Annals - Manufacturing Technology, Vol. 53, No. 2, pp. 643-655.

No.	Activity of the overview in Section 5.2.2	Related activities from Blanchard & Fabrycky (2014)
1	Defining and specifying requirements	Definition of quantitative and qualitative reliability/maintainability requirements Allocation of reliability/maintainability requirements
2	Everyday discussions	
3	Design reviews	Formal design reviews and approvals
4	Analysis of wear and failure behavior	Reliability analysis and trade-offs Reliability predictions Reliability test and evaluation
5	Analysis of maintenance performance	Reliability analysis and trade-offs Reliability predictions Maintainability analysis and trade-offs Maintainability predictions Maintainability demonstration
6	Testing activities	Reliability test and evaluation Maintainability test and evaluation
7	Maintenance service design activities	Maintenance concept Maintenance engineering analysis
8	Making improvements during the pilot run	reliability/maintainability data collection, analysis and corrective action
9	Developing upgrades/improvements during the use and support life cycle phases	System/product modifications
10	Gathering and analysis of data and feedback	Reliability/maintainability data collection, analysis and evaluation

Table A10.1: Overview of how the activities that are prescribed by Blanchard & Fabrycky (2014) to address reliability and maintainability can be related to the overview of development activities that is presented in Section 5.2.2.

No.	Activity of the overview in Section 5.2.2	Related activities from Takata et al. (2004)
1	Defining and specifying requirements	
2	Everyday discussions	Maintainability design
3	Design reviews	Maintainability design
4	Analysis of wear and failure behavior	Maintainability design
5	Analysis of maintenance performance	Maintainability design
6	Testing activities	
7	Maintenance service design activities	Maintenance strategy planning Maintenance task control
8	Making improvements during the pilot run	Improvement of maintenance and products
9	Developing upgrades/improvements during the use and support life cycle phases	Improvement of maintenance and products
10	Gathering and analysis of data and feedback	Evaluation of maintenance results

Table A10.2: Overview of how the activities that Takata et al. (2004) prescribe to address maintenance can be related to the overview of development activities that is presented in Section 5.2.2.

Appendix 11 - A set of design-for-maintenance guidelines

The appendix contains the set of design-for-maintenance guidelines that is developed to support developers in addressing maintenance aspects. This is described in Section 6.4. Figure A11.1 and A11.2 depict the front and back side of the leaflet, respectively.

DESIGN FOR MAINTENANCE - A SET OF DESIGN GUIDELINES

Design for Maintenance is an approach to influence the maintenance activities through the design of the equipment. This set of guidelines serves as a tool to apply Design for Maintenance in practice. The guidelines describe various ways how these future maintenance activities can be influenced. Applying the guidelines can help to reduce the number of maintenance activities, to make them easier to execute or to decrease the logistic support time that is required for them.

The guidelines are divided into three categories:

Guidelines to enhance maintainability

Guidelines that focus on designing equipment that can be repaired quickly and easily

Guidelines to enhance reliability

Guidelines that focus on designing equipment with a low failure rate

Guidelines to enhance supportability

Guidelines that focus on designing equipment that is easy to support

Whether or not the individual guidelines are useful to apply, depends on the situation in which the equipment is used. For a number of them, trade-offs between the advantages and the involved cost should probably be made. The set of guidelines is meant as a tool to start a discussion about the different design possibilities during the development process.

Guidelines to enhance maintainability

Use materials that do not prolong maintenance activities
Avoid non-corrosion resistant materials in moist environments

Use standard, universally applicable components
They are widely understood, what makes it likely that they are easy to maintain or that technicians know how to maintain them

Use fasteners that accelerate maintenance activities
In the ideal situation, no tools are required to open or remove components

Ensure that the operators of installations are also able to maintain them
Maintainable equipment is often user maintained

Provide sufficient space around the maintenance points
Maintenance personnel should be able to execute maintenance with good posture

Guidelines to enhance reliability

Design-out moving parts
Unnecessary movements need to be avoided

Avoid unnecessary components
Limit the number of components by eliminating the non-essential ones

Avoid non-rigid parts / avoid rigid parts
Use tubes instead of hoses / use hoses instead of tubes

Design for understressed use
In normal situations, the system is used at less than full capacity

Provide redundancy
Standby systems or components can take over the operation when necessary

Overdesign components
Dimension critical components larger than minimally required

Guidelines to enhance supportability

Use standard, universally applicable components
Those are widely available

Avoid that expensive spare parts need to be held in stock
In order to reduce the inventory costs

Minimise the number of different types of fasteners
Only those need to be held in stock

Save useful life time data
The saved information can be used for planning maintenance or improvement of the design

Avoid that secondary tasks consume a lot of time
The main activity is executing maintenance

Design for the use of standard tools
Every technician is able to execute maintenance by having a standardised tool kit

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Figure A11.1: Front of the leaflet with design-for-maintenance guidelines

Guidelines to enhance maintainability (continued)	Guidelines to enhance reliability (continued)	Guidelines to enhance supportability (continued)
Design equipment in such a way that it can only be maintained in the right way <i>An unambiguous design induces that no mistakes can be made when executing maintenance</i>	Choose materials that can withstand environmental influences <i>The equipment should withstand the environmental conditions in which it is used</i>	Do not use materials that affect user's and technician's health <i>Avoid corrosive chemicals for lubricants and cleaning products</i>
Components that are regularly replaced need to be easy to handle <i>Standard size and weight, no sharp edges and easy to transport</i>	Do not use coated, painted or plated components <i>They need to be maintained to keep them in good condition</i>	Design the system in such a way that adequate forecasting of maintenance is possible <i>Little variability in mean times to failure of components enables preparation of an adequate maintenance planning</i>
Guarantee safety by the design itself <i>Instead of using warning labels and colour codes</i>	Use components and materials with verified reliability <i>Proven technology minimises the chance of unexpected system behaviour</i>	Build monitoring equipment into the system <i>In order to know if maintenance needs to be executed and to reduce the time for isolating faults</i>
Design modular systems <i>Modular systems enable complete replacement of a broken module to repair it at a different place</i>	Design robust interfaces between components <i>The interaction between components has a strong influence on the reliability of the system</i>	Ensure that as few as possible technicians are required to perform a maintenance task <i>Fewer personnel has to be available at the moment maintenance needs to be executed</i>
Use standard interfaces <i>To enable quick connection between modules and sub-systems</i>	Use parallel subsystems and components <i>Systems containing parallel subsystems, each with the same function, are less likely to fail completely</i>	Personnel with a variety of backgrounds should be able to execute maintenance <i>For executing maintenance one should not depend on a single employee</i>
Design the weakest link <i>Every system has a weakest link, which should be a relatively cheap and easily replaceable component</i>	Distribute workload equally over parallel subsystems or components <i>Wear, and therefore behaviour, of both systems or components will be the same</i>	Provide understandable maintenance instructions <i>The instructions need to be understandable by everyone who is expected to perform the required maintenance</i>
Position components that often need to be maintained at an easily accessible place <i>Location of components could be based on the number of times they need to be maintained</i>		
Position the maintenance points close to each other <i>The maintenance location is known beforehand</i>		
<p>The guidelines are explained and illustrated in:</p> <p>Mulder, W., Blok, J., Hoekstra, S., Kokkeler, F.G.M.(2012). <i>Design for maintenance. Guidelines to enhance maintainability, reliability and supportability of industrial products</i>. Enschede, University of Twente</p> <p>Any remarks or questions can be emailed to w.mulder@utwente.nl</p>		
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Figure A11.2: Back of the leaflet with design-for-maintenance guidelines

Acknowledgements

At this last page of my dissertation, I wish to thank everyone who in one way or another helped me with the completion of this work. In particular, I would like to thank my supervisors Juan, Leo and Rob. Thanks for the possibility to work on the research project and for all your guidance, help and encouragement over the past years. A special thanks also goes to the experts from the companies who I interviewed and to them who participated in the feedback sessions and have provided feedback to my research findings. Thanks a lot for your willingness to share your knowledge. It would have been impossible to conduct the research without your help. Last but not least I also would like to thank all my colleagues from the department Design, Production and Management of the University of Twente. I have really enjoyed being part of the group. Thanks everyone for the nice moments at the university and during all the other activities that we have undertaken together.

Enschede, May 2016

Wienik Mulder