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TOWARDS STRUCTURED INTEGRATION OF MAINTENANCE KNOWLEDGE IN INDUSTRIAL EQUIPMENT DESIGN

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ABSTRACT

Industrial equipment requires maintenance to remain operational. The level of maintenance that is required, and how easily it can be executed, is affected by the characteristics of the equipment. Therefore, design decisions have a strong influence on the effectiveness and efficiency of the maintenance process. Ideally, the design of the equipment should be aligned with the design of the maintenance service. Relevant knowledge about the relationships between them is available in both the literature and in practice. It is essential to bring this knowledge into the equipment design process, but suitable design support for this remains lacking. Therefore, we propose to conduct research on how this knowledge can be systematically integrated into the design process. The final goal of the research is to develop design support that leads to an improved quality of design decisions, so that production systems with an increased life cycle performance will be achieved.

Keywords: product-service systems, early design phases, design for X, maintenance knowledge, industrial equipment

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1 INTRODUCTION

Industrial equipment requires maintenance to stay operational. Maintenance activities strongly influence the lifetime performance of the production systems in which they are used. This is especially relevant in capital-intensive industries, such as the semiconductor, electric power generation and railway industries. Examples of equipment used in these industries are photolithography systems, power generation equipment and trains. In these industries, maintenance activities strongly influence the life time performance in two ways. Firstly, the maintenance costs can add up to several times the initial investments and, therefore, have a substantial effect on the life cycle costs. For example, costs of maintaining a passenger train during its lifetime are typically one and a half times the initial investment (Van Dongen, 2011). Secondly, maintenance activities have a significant impact on the operational availability of the equipment itself, namely the periods for which the aforementioned train is available for passenger service.

Improving the life cycle performance of production systems, in terms of maintenance efforts, can be achieved through improving the maintenance service, the equipment design, and through a combination of the two. Improving the maintenance service is often addressed in the operations management and operations research literature. For example, Pintelon and Puyvelde (2006) discuss the development of maintenance concepts in order to execute maintenance both more effectively and more efficiently. Improvement of the design can be achieved through the application of DfX approaches, such as design for maintainability, discussed by, for example, Dhillon (1999). A trend for the improvement of the combination of both, is the integrated development of products and services, also termed the development of industrial product-service systems (Meier et al., 2011). In such an approach, the interrelations between the physical product and the non-physical services, including maintenance, need to be considered proactively during the development process (Aurich et al., 2006).

In this paper, we explore how the design of industrial equipment influences the maintenance process, and how knowledge about the relationship between equipment design and the maintenance process can be addressed during the equipment design process. Furthermore, we describe the research that we will carry out in order to develop support that assists in integrating this knowledge into the equipment design process. The goal of the paper is to first present the indications from both literature and practice that have led to our research plans and then to present the plans themselves.

The remainder of this paper is structured as follows. Section 2 gives a background from the literature about how maintenance can be addressed through design and how maintenance knowledge can be used for this. Section 3 then illustrates the importance of systematically integrating this knowledge in the development process by an example from practice. Next, Section 4 presents our research plans. Finally, our conclusions are presented in Section 5.

2 BACKGROUND

To optimize the effectiveness and efficiency of the maintenance process, it is essential that the design of the equipment and its maintenance service are considered simultaneously. This topic is addressed within various types of literature. This section provides background information from the literature for understanding of the research plans presented in this paper. Section 2.1 deals with the design of equipment and its maintenance service, Section 2.2 addresses the approaches that are available for such design and Section 2.3 elaborates on the use of maintenance knowledge for improvement of such design.

2.1 Design of equipment and maintenance service

Equipment design influences the maintenance activities in three ways. Firstly, it influences how often the equipment fails and how well the need for maintenance can be predicted. This is usually measured in terms of the product's reliability, the probability that the product will perform in a satisfactory manner for a given period when used under specified operating conditions (Blanchard and Fabrycky, 2011). Secondly, the equipment design influences the ease, accuracy, safety, and economy of performing the maintenance actions. These represent the product's maintainability (Blanchard and Fabrycky, 2011), and have a strong influence on the time and labor hours that are required for the maintenance tasks. Design decisions on the selected materials, the dimension of the components, and architecture of the equipment determine the equipment's reliability and maintainability. An increased reliability can, for example, be achieved by using redundant components, and increasing the

maintainability may be achieved by positioning maintenance points at easily accessible locations (Dhillon, 1999 and Mulder et al., 2012). Thirdly, equipment design also determines which maintenance resources are required to perform the maintenance task. For example, it depends on the weight and size of the equipment's components how many maintenance workers are needed to exchange a component. The level of difficulty of the maintenance tasks determines the level of training required for the technicians. And when sensors are built in for monitoring the condition of the installations, in order to better predict the maintenance activities, personnel and equipment is required for processing the retrieved information.
Selection of the maintenance resources forms a part of *Maintenance service design.* Maintenance service design also includes tasks as the selection of workshops, tooling, personnel and spare parts. Ideally, this is done simultaneously with the design of the equipment. This is both the vision in the concept of Integrated Logistic Support (Jones, 2006) and Product/Service-System (PSS) design. A lot of relevant recent research is carried out under the theme of PSS design. PSS is an integrated product and service offering that delivers value in use (Shebab and Roy, 2006). A PSS combines a physical product and a non-physical service, so that systems can be optimized for the desired outcome, for example a particular production output. Within PSS design, maintenance is one of the services of importance. It has the goal to increase equipment availability and to extend the life time of the equipment, in order to increase production output while minimizing the total life cycle costs.

2.2 Design approaches for equipment and maintenance service design

In the literature many design strategies, methods and tools are discussed that deal with the design of products and services. In the context of PSS design, three strategies are distinguished (Aurich and Fuchs, 2004):
1. Product-oriented PSS design: focusing at offering a standalone product, sale of guaranteed product functions.
2. Use-oriented PSS design: focusing at offering service enhanced products, sale of the function fulfillment of the product.
3. Result-oriented PSS design: focusing at offering integrated products and services, sale of the use of the product.

Dependent on the desired PSS offering of an equipment manufacturer, one of these strategies can serve as a guideline for implementing PSS. To design products and service according to one of the strategies, several design approaches exist to support de designer. Tan et al. (2007) have researched the relevant design approaches. As Figure 1 shows, they vary from purely product-oriented to merely customer-oriented methods and tools. For product-oriented PSS design, the product-oriented approaches are the most important. These approaches focus on the operational activities of maintenance and repair, and include for example design for maintainability and reliability analysis methods. For use-oriented and result-oriented PSS design, also the customer-oriented approaches will be helpful. These aim at supporting the design of the service itself, giving more attention to business strategies and supplier-customer relationships than to the design of the physical products.

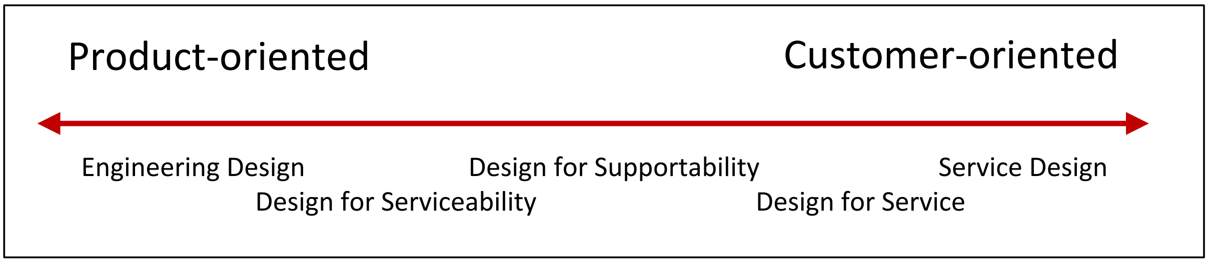

Figure 1. Different types of service-oriented development approaches (based upon Tan et al., 2007)

Especially product-oriented approaches are much discussed in literature. Two of them are: design-out maintenance and designing for maintenance (Markeset and Kumar, 2003). The former focuses on minimizing the maintenance actions that are required to keep the product in good condition. The latter has the goal to simplify the remaining maintenance actions. The research that we propose, in Section 4, is mostly related to *use*- and *result-oriented PSS design* and *Design for Service* design approaches.

2.3 Use of maintenance knowledge for equipment and maintenance service design

It is commonly agreed that knowledge about the use of products can help to improve current or to develop new products and services (Goffin, 2000). Information and data on the use and failure patterns of equipment can help to obtain insight into the failure behavior of equipment. Analysis of time and labor hours required for performing maintenance tasks can give an improved understanding of the time consumption of maintenance activities and the efficiency of the maintenance process. Also valuable information resides in company employees in the form of skills, know-how, capabilities and feeling, the so-called tacit knowledge (Nonaka and Takeuchi, 1995).

How to gather, store and analyze this information about products and services, is a topic addressed in life cycle management literature. In the context of maintenance knowledge, Takata et al. (2004) propose, based on the work of Takata (1999), the three feedback loops for maintenance knowledge that are represented in Figure 2. The first loop is for controlling routine maintenance work, the second one for improving the maintenance strategy planning and the third one for continuous improvement of the product during its complete life cycle.

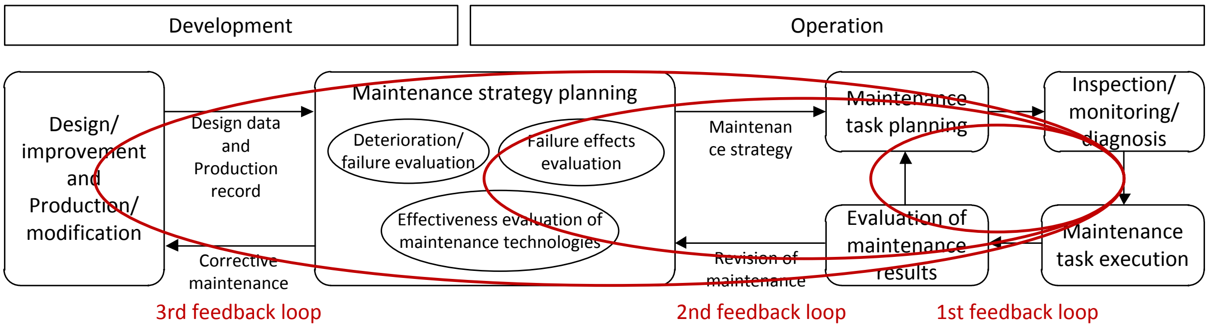

Figure 2. feedback loops for maintenance knowledge (based upon Takata et al.,1999)

The value of using maintenance knowledge in design is also demonstrated by case study research, performed by Doultsinou et al. (2009). In the context of developing PSS, they develop a service knowledge reuse framework, in which service knowledge related to both the service operation and to product design is classified. The framework helps to identify service tasks that could be made easier to perform, by making changes in the design of the products.

2.4 Concluding remarks

It is important to consider the design of equipment and its maintenance service simultaneously. This helps to create equipment and maintenance services that are well-aligned and thus optimal contribute to a well performing production system. To create such systems, knowledge that is available about the use and maintenance of the equipment can have a key role. This will also be illustrated in the example from practice in the next section. The research we will carry out will be based on these topics.

3 EXAMPLE FROM PRACTICE

To illustrate the relevance in practice, this section presents an example from industry. The example shows that systematically using knowledge would have saved engineering time and costs. The information and data presented in this section were obtained through interviews with company engineers.

3.1 Description of the design change

Since 2009, the Netherlands Railways (NS) has operated the Sprinter Lighttrain (see Figure 3) for regional and urban services in the Netherlands. About 130 new train sets were purchased to replace a number of existing train sets. During the development of this train, a number of design changes were made in response to input from the future maintenance provider of the trains, NedTrain, which is a wholly-owned subsidiary of the Netherlands Railways. An example of such input led to the redesign of the construction that mounts the compressor on the underside of the train. Every Sprinter train is fitted with one compressor that needs to be exchanged, on average, seven times during the thirty years lifetime of the train. The compressor, shown in Figure 4, was initially fitted at ninety degrees with respect to the driving direction.

Figure 3. NS Sprinter train

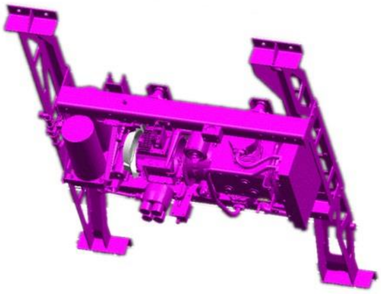

Figure 4. Compressor and construction of its mounting

3.2 Effects of the design change on maintenance times and costs

Maintenance of Sprinter trains is carried out at the workshops of NedTrain. In these workshops varies types of trains are maintained using the available equipment and personnel. The initial design of the compressor and its mounting construction made it impossible to exchange the compressor with the train on rails above a service pit. For replacement, special lifting equipment, which is available in the workshop, would have been required. However, using this special lifting equipment is considerably more expensive and also requires additional preparation time. Figure 5 and Figure 6 show the maintenance times and cost respectively for exchanging a single compressor. They show that following the redesign, the maintenance time is more than halved and the maintenance costs are about a third. The total expected savings over the lifetime of the whole Sprinter fleet is about 700,000 euros. Less maintenance time also means extra availability of the train for transporting passengers.

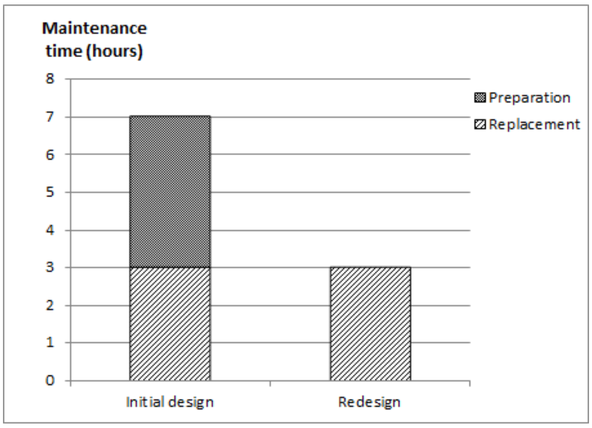

Figure 5. Replacement time compressor

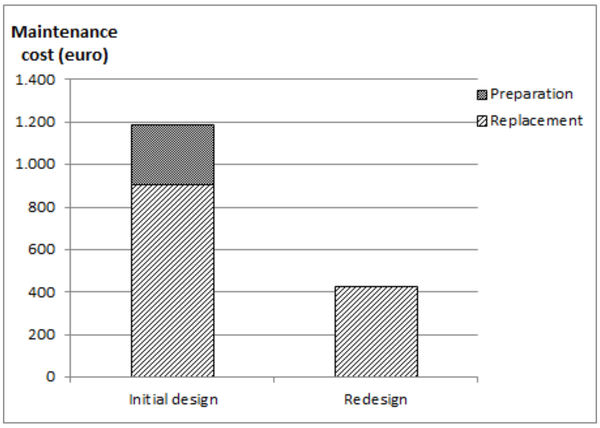

Figure 6. Replacement cost compressor

3.3 Effects of the design change on the availability maintenance equipment

The special lifting equipment, that would have been necessary for replacement of the compressor in the initial situation, is mainly used for exchanging bogies. Because such equipment is very expensive in comparison with a standard pit, each workshop only has one. The utilisation rate of this equipment is already about 85 per cent. Using the equipment for exchanging the compressors would have increased this to more than 90 per cent. Planning maintenance activities, for the exchange of both compressors and bogies, would have become much more difficult. In cases of unexpected failure of a compressor, the probability of the equipment not being available would have been high. Standard pits, on the other hand, have sufficient availability.

3.4 The development process

The possible design improvements were only identified late in the development process. About 75 per cent of the design work was already done when the engineers employed by the maintenance provider took a look at the consequences of the design on the future maintenance activities. Studying the technical drawings, they detected a number of design constraints that would make future maintenance activities much more expensive, among which was the position of the compressor. This led to a delay of four weeks in the development process. The main learning point taken from this by the company was that the knowledge from engineers that have experience in maintaining the trains should be recognized during the early stages of the development project. Therefore, the requirements for maintenance must be functionally specified in the new development process. When presenting the developed train, the manufacturer has to provide information about the expected maintenance times and costs. The maintenance provider provides the necessary information about the workshops, the available equipment and the time it takes to execute maintenance activities.

3.5 Concluding remarks

The example in this section shows that maintenance knowledge was not fully addressed during the development process. Within this particular project, it only delayed the development process. However, it could have easily resulted in the development of a train with unnecessarily high maintenance costs and reduced availability. It is important that in future development projects such knowledge will be more systematically brought into the design process. Our research, described in Section 4, will contribute to developing support for doing this.

4 RESEARCH PLANS

As stated in Section 2, and illustrated by the example in Section 3, knowledge about the maintenance and operation of equipment is valuable for the design of both equipment and its maintenance service. Our initial research indicates that a number of research projects have been worked on developing design support to achieve this. In order to contribute to the development of effective design support, we will continue to conduct research on this topic within a selected range of industries. We describe our research goal and research questions in Section 4.1 and our research methodology in Section 4.2.

4.1 Research goal and research questions

The ultimate goal of our research is to develop design support that helps designers in industry to develop equipment that can be maintained both effectively and efficiently, thus helping to improve the life cycle performance of the entire production system. Figure 7 shows how we expect to achieve this. We assume that (1) the quality of design decisions can be improved by bringing in knowledge about maintaining and operating equipment into the early development stages and (2) that this can be done by the development of new or the improvement of existing design support. This will improve the alignment of the equipment's design with its future maintenance service. Our assumptions are based on examples found in industry, such as the example described in Section 3, and findings from the literature as described in Section 2. Moreover, this is confirmed by Goffin (2000), who has done research into the factors that prevent companies from developing products that are easy and efficient to support. Among other factors, he mentions that support requirements are typically considered too late in the development process and that people in the field usually do not have the opportunity to influence the product design.

To develop suitable design support, we need a profound understanding of (1) the influence of equipment design on the maintenance process and (2) how knowledge about this relationship can be exploited in equipment development. The two research questions we will address are:

1. Which aspects of the equipment design influence the maintenance process and what is their effect in a particular operational environment?

2. How can designers be supported during the early development stages to design equipment that can be maintained both effectively and efficiently?

2a. What knowledge about manufacturing and maintenance could and should be brought into the early development stages and what is the effect of doing this?

2b. What type of design support helps in the design of equipment that can be maintained both effectively and efficiently?

As the research questions suggest, the focus will be on the early development stages. The decisions made in those stages are considered to have the greatest impact on the final performance of the developed product. These early design stages are generally used to create conceptual design solutions. Such solutions are, according to Hansen and Andreassen (2005), proposals for products and services that describe the most important features of and requirements for the final offering. When designers are able to both generate different concept solutions and adequately assess the performance of such solutions, well-considered design decisions can be taken. The knowledge that we propose to bring in the design process and the design support should contribute to this.

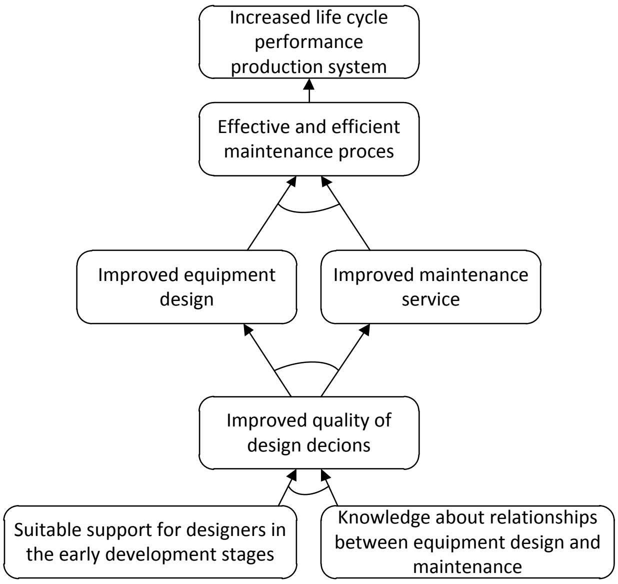

Figure 7. Intended effect of the research

4.2 Research methodology

To address the research questions and to develop the necessary design support, we will follow the Design Research Methodology (DRM) proposed by Blessing and Chakrabati (2009). DRM has four research stages: (1) *research clarification* for finding indications and formulating a worthwhile research goal; (2) *descriptive study I* for describing the existing situation by reviewing the literature and/or an empirical study; (3) *prescriptive study* during which support is developed; and (4) *descriptive study II* for investigating the impact of the support. The research presented in this paper is the result of the research clarification stage. The research activities for the next stage, namely descriptive study I, are described below. Research relating to the other stages will be carried out later on and will be addressed briefly at the end of this sub-section.

The purpose of descriptive study I is to describe the existing situation. To achieve that, both a literature study and empirical research will be conducted. The research in this stage will focus on a specific range of systems: production systems used for the production of discrete products that have high availability requirements and high down-time costs. The equipment used in these systems, contains mechanical and electrical components and is located at fixed locations. The empirical study consists of several interviews with both the manufacturers and the maintenance providers of the equipment, which can be the users. By investigating the design of the equipment from both perspectives, we will learn what knowledge has already been brought into the design process and what knowledge still needs to be brought in. This will help us to understand the relationship between equipment design and maintenance. Also, it is likely that examples will be found of both well and poorly aligned design of equipment and its maintenance service.

Combining the findings from the literature study and the empirical research should give a good understanding of how maintenance is currently considered during equipment design. Moreover, we expect to be able to define the most important areas of investigation for improvement in the next stages of the research.
The further development of the research in the *prescriptive study* depends on the outcomes of the research described above. Possibilities are that we focus on the development of a method or tool for knowledge integration into the design process of one of the companies, or that we focus on the development of a workshop that helps service technicians and designers to share maintenance knowledge.

4.3 Concluding remarks

The final purpose of the presented research plans is to develop support for designers of equipment for the capital intensive industry. In order to develop such support, it is important to have a profound understanding about both the factors that influence the maintenance activities and the factors that influence the design process. We expect that the proposed research will help to get these insights. By conducting research from both the perspective of designing equipment and maintaining equipment in different companies, both good and bad points of current practices will be revealed.

5 CONCLUSION

In this paper, we have discussed how the design of industrial equipment can be considerably improved when knowledge about maintenance is brought into the equipment design process. This knowledge is generally available in industry, as well as in other research fields concerned with the relationships between equipment design, maintenance and operation. Using this knowledge in the equipment development process will help to design equipment that can be maintained more effectively and more efficiently. In various types of literature this topic is addressed, and the importance is illustrated by the Sprinter train example from practice. The example shows that not addressing such needs systematically, can easily lead to the development of equipment that causes unnecessarily high maintenance costs and reduced availability of the equipment. In recent research, attempts have been made in developing methods and tools for addressing the use of this knowledge systematically in the design process of products and services.
The goal of the research that we propose is to contribute to the development of design support for integrating maintenance knowledge in the equipment design process. Research will be conducted from both the perspective of equipment design and the perspective of operating and maintaining equipment. Research from those both perspectives is expected to lead to a more profound understanding of (1) the influence of equipment design on maintenance; and (2) how maintenance is currently addressed in the design process. Because research will be performed in various companies, it is likely that both good and poor practices will be uncovered. Analyzing such practices will help to develop design support that will lead to an improved quality of design decisions, so that design of equipment and its maintenance service are better aligned. This is expected to lead to a more effective and efficient maintenance process, ultimately resulting in production systems with an improved life cycle performance.

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