

SUPPORTING INDUSTRIAL EQUIPMENT DEVELOPMENT THROUGH A SET OF DESIGN- FOR-MAINTENANCE GUIDELINES

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1. Introduction

Companies that develop and manufacture industrial equipment, increasingly need to offer solutions that perform well over their whole life cycle. Their customers –for example capital intensive industries– use such equipment for producing other goods or to provide services. In order to be competitive, they demand systems that have an optimal balance between the system’s availability, the initial investment, and the expected future cost for operation, maintenance and disposal. Also, the equipment manufacturers themselves are searching for business strategies with larger margins by offering integrated solutions of products and services, often referred to as industrial product-service systems (see [Cohen et al. 2006] and [Meier et al. 2010]). The design of the equipment is a key issue in helping to achieve systems that are optimally prepared for, among others, the future maintenance activities. Decisions made on, for example, choice of materials, choice of parts, dimensions of parts and the way how parts are assembled, influence how often maintenance is required and how easily maintenance tasks can be performed and supported. Therefore, it is essential to address the maintenance aspects during the development process of industrial equipment.

There exists a considerable amount of literature that shows how maintenance can be addressed in the development process and which methods and tools are available to support this. Overviews and discussions of such methods and tools can be found in, for example, Desai and Mital [2006] and Tan et al. [2010]. Although a lot of knowledge is available, we know from interviews that we have conducted with industrial partners and from the researched literature [Goffin 2000], that design-for-maintenance (DfMain) aspects do not always get appropriate attention. As a consequence, products offered by manufacturers are not always optimally designed so that they can effectively and efficiently be maintained and supported. There may be various reasons for this, for instance; the difficulty to oversee the and maintenance activities during the long life time of the equipment, the limited focus that these issues get compared with other design issues, and the number of ideas that are considered on how the maintenance activities can be influenced through design.

In this context, we have initiated a research project in which we investigate how equipment developers design for maintenance in practice and how they can be supported in improving that. The goal of our research is to support equipment developers in improving their design-for-maintenance practices, making these activities more effective and/or more efficient. We do so by developing the support, and evaluating it in practice. Such support could also be an improved version of already existing design support. This paper presents such research. Based on guidelines that can be in the literature and in industry, we have developed a a set of design-for-maintenance guidelines that is applicable to a wide

range of industries. We have particularly paid attention to the way in which the guidelines are presented to the future user in order to get such support adopted in practice. The developed set of guidelines aims to attract attention in companies to DfMain aspects, and it aims more specifically to improve idea generation.

The set of guidelines has been developed in multiple iterations. The first version was prepared based on several literature sources and our own knowledge. Based on this version, a considerable number of small changes and improvements have been made. These were based on a number of discussion sessions with involved industrial partners and colleague researchers in the field of maintenance. In this paper, the whole development process is systematically described, by means of four development stages: problem analysis, conceptualisation, realisation and evaluation. These four stages are described in Sections 2 to Section 5. In Section 6 we present our conclusions. The complete set of guidelines is supplied in the Appendix.

2. Problem analysis

The goal of our research is to develop support that helps equipment developers to design for maintenance in practice. To be able to develop such support, we firstly need to understand what factors are important to address and secondly how these factors can be influenced during the development process. Figure 1 shows an overview of the factors of interest in the context of this project and the causal relationships between them. The factors of interest are divided into four categories, represented by the four layers in the diagram of Figure 1: factors related to (1) the company's business, (2) the product, (3) the development process, and (4) the design support to be developed. The diagram shows how we aim to influence the design decisions via the development of support in such a way that they contribute to the success of the product and their businesses. In the remainder of this section, the relationships between the factors of interest in our research are explained.

The top of the diagram shows the factors that represent the company's success: satisfying customers with a competitive product and making profit. As already stated in Section 1, availability issues are important selection criteria in the equipment selection processes of the customers. The product related factors that have a strong influence on the expected availability are three of its properties: the product's maintainability, reliability and supportability. The combination of these properties influences how effectively and efficiently maintenance activities can be performed. Based on our discussions with industrial partners we have identified four factors in the design process that could be supported to improve design decisions on DfMain aspects. These are represented by the four *key factors* in the diagram of Figure 1:

1. *The degree to which attention is paid to DfMain aspects.*
Design for maintenance does not always get appropriate attention. Other design aspects, for example the product's functionality, are getting full attention of members in a project team. Also, it happens that the team members are not aware of the importance of addressing DfMain aspects.
2. *The number of DfMain ideas that are considered.*
There are various ways in which reliability, maintainability and supportability can be influenced through design. Considering various ideas could lead to solutions which are not the standard chosen ones.
3. *The quality of the design reviews on DfMain aspects.*
Design reviews on DfMain aspects, for example via the use of checklists, could be made more complete and more accurate.
4. *The accuracy of modelling the expected maintainability, reliability and supportability of the equipment.*
The more accurate these properties can be modelled, the better the effect of a design choice can be made visible.

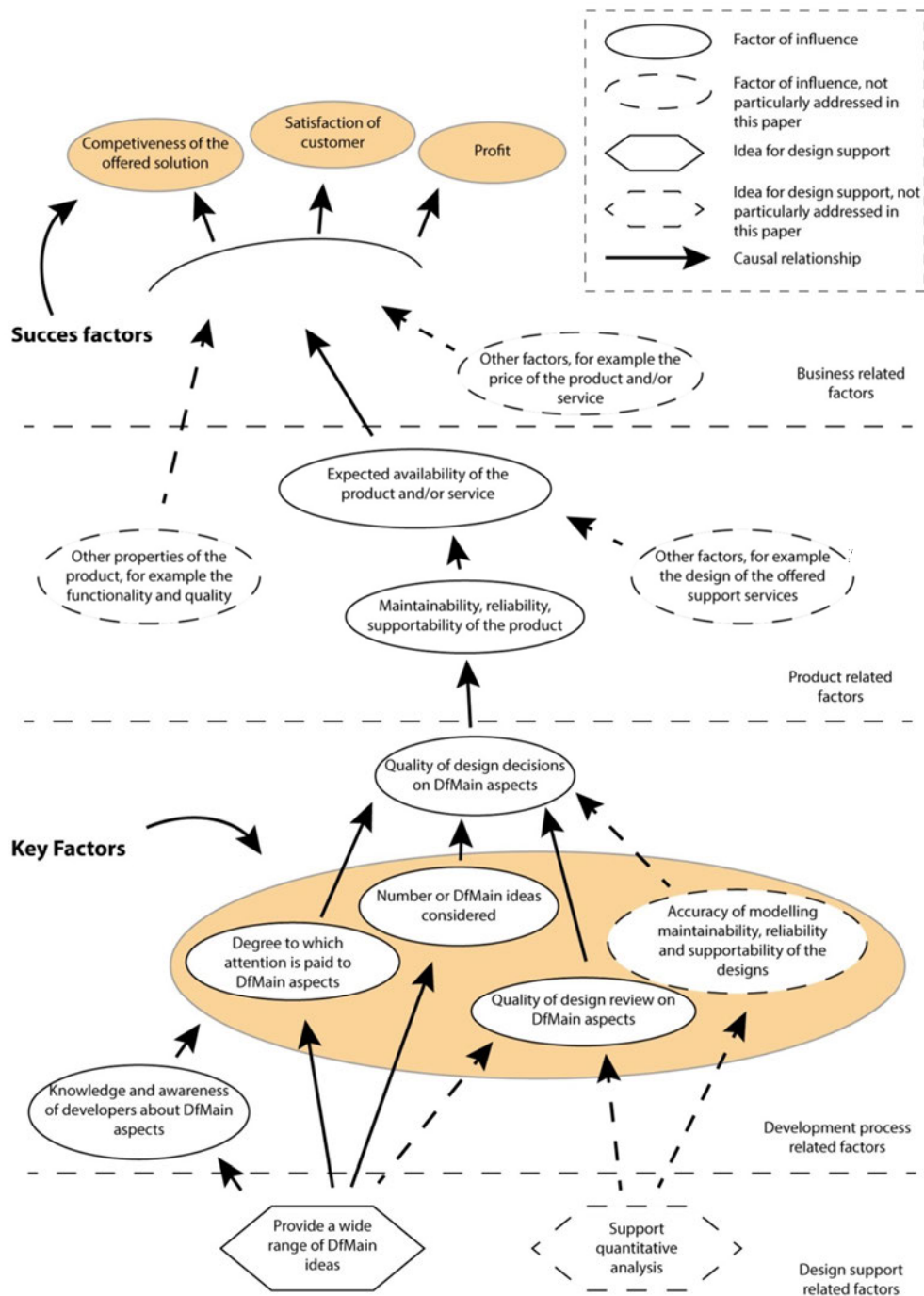


Figure 1. Cause effect diagram showing the desired effect of the design support

To support these factors within the development process, different types of support could be developed. In the diagram of Figure 1 two ideas for design support are represented: (1) the provision of a wide range of DfMain ideas and (2) the development of a quantitative analysis model that aims to improve the modelling of the reliability, maintainability and supportability. In this project, we have chosen to work on the first one, a qualitative approach. Such support could also help to generate awareness and to increase the knowledge about DfMain aspects in development teams, which is a starting point for improving the other factors. Also, in the (early) development stages it is difficult, or impossible, to correctly model the maintainability, reliability and supportability. We were not sure about the chance to successfully develop such support that could be implemented and tested in practice in the short term.

3. Conceptualisation

The chosen support idea for further development is to ‘provide a wide range of DfMain ideas’. This section describes the results of the second stage in the support development process: the conceptualisation. Firstly, the requirements for the support are listed and secondly, the line of reasoning that brought us to the idea of developing a set of guidelines is described.

The main requirements, used as starting point for the development of the support are given below. The first part of the requirements represents the functions that the support should have. These functions are identified as key factors in the problem analysis phase (Section 2). The second part of the requirements represents the effect that the use of the support should have on the properties of the product. These properties are also identified in the problem analysis phase: the product related factors. The third part of the requirements deals with the area in which they will be used. We assumed that, to make implementation of the support successfully, it would be particularly important to ensure that implementation in practice will be easy.

Requirements part 1 - Intended functions of the support:

- The degree of attention for DfMain aspects during the development process should be increased.
- The number of DfMain ideas that is considered in the development process should be increased.
- The qualitative design review on DfMain aspects should be improved. (this is a factor that also can be supported by ‘providing a wide range of DfMain ideas’, but in our research, and the remainder of this paper, it is not explicitly addressed)

Requirements part 2 - Intended effect of the support:

- The use of the support should lead to improvement of the product on its (combination of) maintainability, reliability and supportability properties.
- The use of the support should lead to improved design decisions contributing to the total performance of the product.

Requirements part 3 - Area of use:

- The support should be suitable in the development process of different types of industrial equipment.
- The support should be usable without the need for changing the existing development process.
- The support should be usable as addition, or to be incorporated, into the current working approaches of the equipment developers.

The choice to develop a set of guidelines to ‘provide a wide range of DfMain ideas’ is based on two characteristics that guidelines have. At first, guidelines represent explicit knowledge that can be used to address specific design objectives. In the context of design for maintenance, they guide in attaining the following design objective: optimising the product’s properties so that it the developed equipment is optimised for the maintenance activities during its life cycle. Secondly, guidelines are easy to incorporate into the current way of working and can support multiple design activities without the need for changing currently used design procedures. The first characteristic could ensure that part 2 of the requirements will be fulfilled. The second characteristic makes the support flexible in its use, what is both desired for fulfilling part 1 and part 3 of the requirements. For further development both the content of the guidelines and the way in which they are presented were considered to be important.

The content of the guidelines should give solution directions that are useful for addressing maintainability, reliability and supportability aspects. These are the product properties that directly influence the future maintenance activities. They influence how often maintenance is required and how easily, quickly and safely the maintenance activities can be performed. Also, the guidelines should be useful for a wide range of industries. This means that the guidelines on the one hand should be sufficiently specific to address the improvement of these properties, but on the other hand should not be so specific that they are applicable only to a particular type of equipment. The selection of guidelines is based on literature search and discussions about them with industrial partners and colleague researchers in the field of maintenance. Not only guidelines in the field of design-for-

maintenance are useful, also guidelines from other fields of study can provide valuable insights. For example, to make maintenance activities easy to perform, (dis)assembly and ergonomics aspects, play an important role. Table 1 lists a number of authors that have provided relevant guidelines in the literature.

Table 1. Selection of the literature used as knowledge source for composing the set of guidelines

Literature	Field of guidelines			
	General design guidelines	Design for maintenance guidelines	Product related guidelines	Guidelines from other fields of study
Dhillon [1999]		X		
Gardner and Sheldon [1995]		X	X	
Irmhan [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

The way in which the guidelines are presented should ensure that implementation in practice will be easy and that developers are stimulated to use them. There are several ways in which the guidelines could be presented. A distinction can be made between computerised or paper-based representation of the guidelines. Computerised tools for providing such guidelines are useful when they can be connected to the software that developers use to translate their design ideas in, for example, a 3D-models of the product. A computer programme can then identify for specific decisions which guideline can be useful and help the designer to apply it. However, the drawback is that such programmes are used in the later design stages, which might be too late for applying certain guidelines. Paper-based representations have the disadvantage that the developer is not forced to read the guidelines and to apply them. However, they have the advantage that they can be independently used of other design methods and tools, and therefore they are also useful in the early design stages. Also, they could easily support during discussions between expert from different disciplines, for example between design engineers and maintenance engineers, which can be an important sources for generating design ideas. Especially the easiness to implement them, and the possibilities to use them in early design stages, has led to the decision for developing paper-based support.

The way in which (the paper-based representation of) the set of guidelines is distributed, is also an factor that has an influence on the actual use. There are several possibilities to distribute it, such as: a poster, a leaflet and a booklet. Each of them has its own advantages. Posters attract the attention at meeting points in an office (for example at the coffee machine) and lead to talks and discussions about the topic. Leaflets can be distributed among employees and draw attention because it is on the developers' desks. A booklet has the advantage that more detailed aspects can be described which is interesting for the persons that would like to study the topic more deeply.

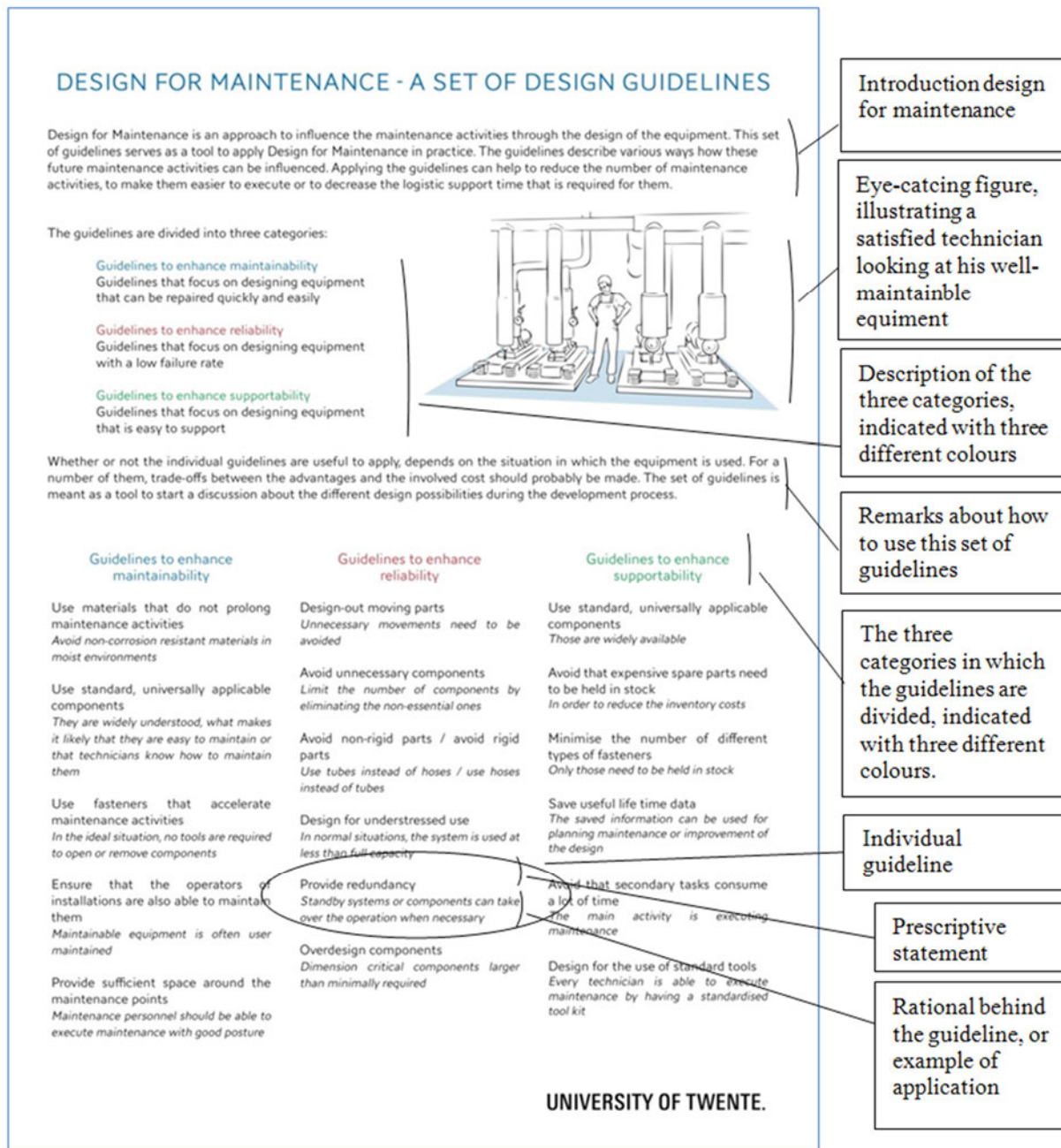


Figure 2. Set of design-for-maintenance guidelines – front side of the leaflet

A leaflet has the advantage over the others that it is easy to distribute, to share and to duplicate, which makes it easy to reach a substantial number of potential users. Therefore, this format was selected as the main part of the support. Additionally a booklet is written to provide additional DfMain ideas for each guideline.

4. Realisation

This section gives a full description of the two parts that together form the support, and how the support can be used in companies. The main part of the support is the leaflet with design guidelines; a booklet [Mulder et al. 2012] accompanies this leaflet.

The front-side of this leaflet is presented in Figure 2, and the back-side is supplied in the Appendix, in order to be complete. Figure 2 also presents how the leaflet is constructed. It starts with starts with a brief introduction explaining the basics of design for maintenance and how the leaflet could be used.

Then the guidelines themselves are described. The guidelines are divided into three categories: guidelines to enhance maintainability, guidelines to enhance reliability and guidelines to enhance supportability. The guidelines give design directions, and should be a starting point for discussions about DfMain aspects. It is possible that, in particular situations, the guidelines contradicts each other or that a trade-off needs to be made between the advantage and the involved costs of applying the guidelines. Also, the structure of the guidelines should stimulate the discussion: the upper part of the guideline gives a prescriptive statement about how to increase reliability, maintainability or supportability. The lower part provides the rationale behind the statement or an example of how it can be applied.

The booklet [Mulder et al. 2012] contains the same guidelines as the leaflet, but two pages are used for each guideline: the guideline is explained and three different sub-areas are given in which the guideline can be applied. Each example is accompanied with an illustration that shows the result of applying, or not applying, the guideline. An example page of the booklet is shown in Appendix.

Implementing the support in practice can be done by distributing the leaflet among the people in the development team that need to address DfMain aspects. In the first place, it is meant as a tool for starting discussions about the different design possibilities (as also mentioned in the introduction part of the leaflet). Another area of application could be the improvement of already used design support tools, for example to update maintainability checklists that are already used in the companies' development projects. Also, the set of guidelines could be useful for communicating with other stakeholders, for example the developers of the maintenance service of the product. To foster successful application, companies are encouraged to think about developing an own version containing guidelines that are relevant for their products and are useful in their development processes.

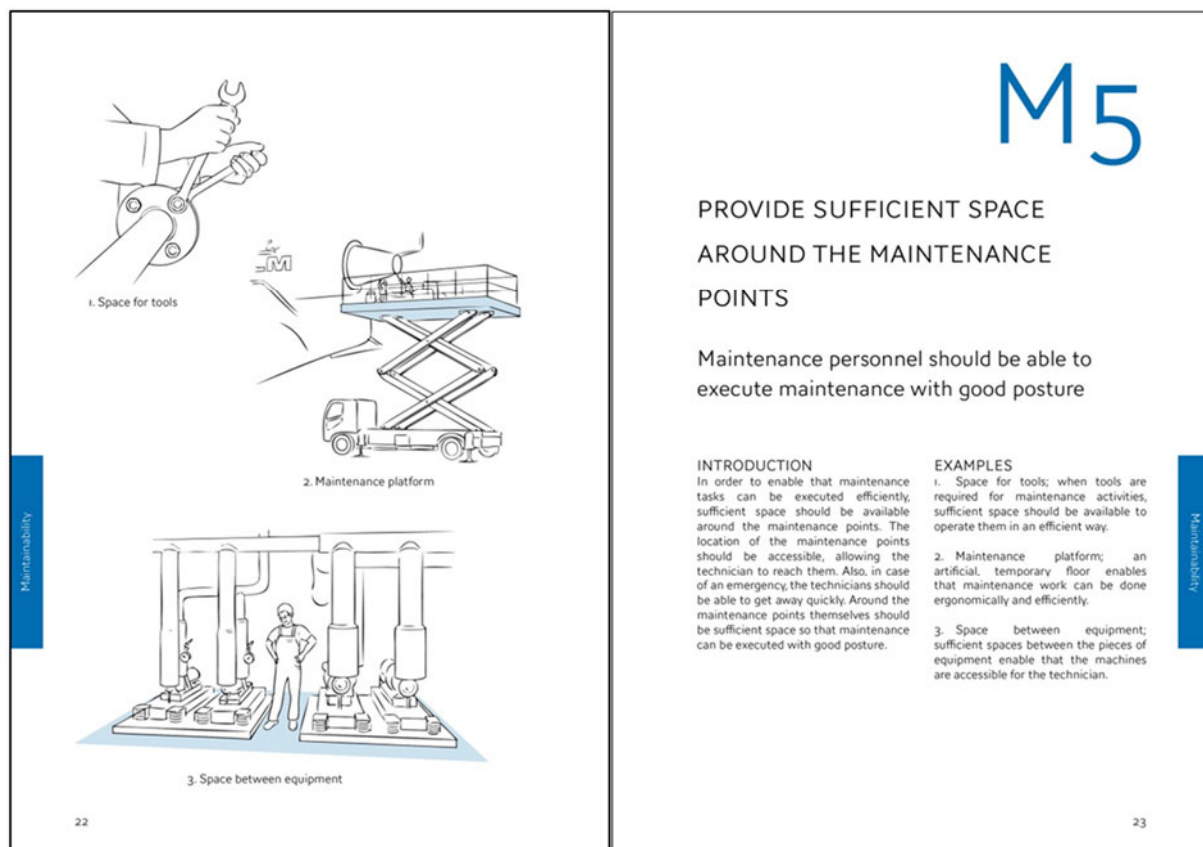


Figure 3. Example of a page in the booklet

5. Evaluation

To evaluate the support and to know whether or not the use of the guidelines is successful, a thorough evaluation study is required. This evaluation is split into two parts. Firstly, during the development of the support we have held two workshops with industrial partners. Secondly, we have planned, but not yet conducted, a thorough empirical evaluation study.

During the two workshops potential users of the support have given their feedback on the set of guidelines. In the first workshop, with one industrial partner, the individual guidelines were reviewed. We examined the usefulness of including the particular guidelines in the set and discussed if particular guidelines should be eliminated or added to the set. Also, it was checked if the guidelines were clearly formulated. This received feedback is used to make decisions on the final selection of the guidelines and to ensure that all guidelines were formulated clearly and understandably. In the second workshop, held with another industrial partner, the guidelines served as starting point in a discussion about how their equipment could be improved on DfMain aspects. They came up with several ideas and positively comment on the work and its usefulness during the equipment development process.

The empirical evaluation study should evaluate the support at three levels. Firstly, the support itself should be evaluated. Secondly, the effect on the activities in the design process should be investigated. Thirdly, it should be evaluated whether or not the use of the support leads to products with improved reliability, maintainability and supportability properties. The starting point for this evaluation will be the listed requirements in Section 3. The support will be evaluated through a survey among a substantial number of equipment developers in Dutch industry. We will provide the set of guidelines to them, accompanied with the booklet, and ask them to fill in a questionnaire.

To evaluate the first level, the support itself, we will focus on both the content and the usability. Evaluating these aspects should give answers to questions, such as: are the guidelines accurate? Are the essential DfMain aspects covered? Are the guidelines understandably formulated? This part of the evaluation will be conducted at both companies developing industrial equipment and companies that use such equipment. The latter category has experience in maintaining equipment and, therefore, can provide insights into the DfMain aspects that should be covered in the set.

Evaluation of the support on the second level, must ultimately lead to an answer at the following two questions: does the use of the support leads to an increased degree of attention for DfMain aspects? And does the use of the support lead to an increased number of DfMain ideas that is considered in the development process? We will evaluate this through asking about the expectance that people have about if, and how, they will use the provided support themselves, for what design activities they expect to use it, and if they have gotten new ideas after studying the guidelines.

To evaluate the support on the third level, if the use of the support leads to improved products on DfMain aspects, is difficult to investigate through such a questionnaire. Therefore, we will not specifically investigate this.

Although this evaluation study is not yet performed, we have indications that the support is useful for the improvement of design-for-maintenance practices. We have distributed the set of guidelines and the booklet to a number of companies. Up to now we have received the feedback that a company has used it to create their own set of guidelines in the format of a poster, and that another company has used it to update their design review checklist. Also, a number of companies have distributed it among their employees. They expect that this will stimulate to make thinking about design-for-maintenance a standard design practice in their development activities.

Besides insights into the support, we also expect that the evaluation study will teach us more about how design for maintenance is currently applied in practice. We expect to learn about what kind of design for maintenance support developers in practice use and what kind of design for maintenance support they consider to be useful. This will provide us useful insights for further research into developing design-for-maintenance support.

6. Concluding remarks

In this paper, we have presented our work on the development of support that helps developers of industrial equipment to design for maintenance in practice. We have identified the key factors in the development process of which we assume that they could be successfully supported: (1) the degree to

which attention is paid to DfMain aspects, (2) the number of DfMain ideas that are considered, (3) the quality of the design reviews on DfMain aspects and (4) the accuracy of modelling the expected maintainability, reliability and supportability of the equipment. To support the first three mentioned factors, a set of design-for-maintenance guidelines is developed. The set can be used in a wide range of industries. The guidelines themselves are not something new. Our contribution is the selection of the total set and the way in which the set is presented. The selection makes the set usable in a wide range of industries. The way they are presented makes implementation in practice easy. Based on feedback that we have received from industry, we have indications that the support is useful. A comprehensive evaluation study, that we have planned, should clarify whether or not this is really the case.

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Appendix: Set of design-for-maintenance guidelines – back side of the leaflet

Guidelines to enhance maintainability (continued)

Design equipment in such a way that it can only be maintained in the right way

An unambiguous design induces that no mistakes can be made when executing maintenance

Components that are regularly replaced need to be easy to handle

Standard size and weight, no sharp edges and easy to transport

Guarantee safety by the design itself
Instead of using warning labels and colour codes

Design modular systems
Modular systems enable complete replacement of a broken module to repair it at a different place

Use standard interfaces
To enable quick connection between modules and sub-systems

Design the weakest link
Every system has a weakest link, which should be a relatively cheap and easily replaceable component

Position components that often need to be maintained at an easily accessible place
Location of components could be based on the number of times they need to be maintained

Position the maintenance points close to each other
The maintenance location is known beforehand

Guidelines to enhance reliability (continued)

Choose materials that can withstand environmental influences

The equipment should withstand the environmental conditions in which it is used

Do not use coated, painted or plated components

They need to be maintained to keep them in good condition

Use components and materials with verified reliability
Proven technology minimises the chance of unexpected system behaviour

Design robust interfaces between components
The interaction between components has a strong influence on the reliability of the system

Use parallel subsystems and components
Systems containing parallel subsystems, each with the same function, are less likely to fail completely

Distribute workload equally over parallel subsystems or components
Wear, and therefore behaviour, of both systems or components will be the same

Guidelines to enhance supportability (continued)

Do not use materials that affect user's and technician's health
Avoid corrosive chemicals for lubricants and cleaning products

Design the system in such a way that adequate forecasting of maintenance is possible

Little variability in mean times to failure of components enables preparation of an adequate maintenance planning

Build monitoring equipment into the system
in order to know if maintenance needs to be executed and to reduce the time for isolating faults

Ensure that as few as possible technicians are required to perform a maintenance task
Fewer personnel has to be available at the moment maintenance needs to be executed

Personnel with a variety of backgrounds should be able to execute maintenance
For executing maintenance one should not depend on a single employee

Provide understandable maintenance instructions
The instructions need to be understandable by everyone who is expected to perform the required maintenance

The guidelines are explained and illustrated in:

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

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