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DEVELOPMENT AND USAGE OF A MECHATRONIC DESIGN PROCESS MODEL WITH FOCUS ON ASSUMPTIONS

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ABSTRACT

Nowadays, mechatronics is included in many technical products and, furthermore, mechatronic products are necessary to fulfil a manifold of needs, wishes and requirements of customers (e.g. precision, performance and functionality). Mechatronic products offer many of these advantages, but in most cases they come at the cost of increasing complexity of the product itself and the related development and design process. Design process models can be used as a support in the design process in order to make complexity better manageable by a structured procedure. An important question is now, how project staff can deal with missing or incomplete information during the design process. Especially at the beginning and between several disciplines of the design process, the lack of information is evident in most cases, because a lot of aspects are not entirely defined in the early phases of design. Missing or incomplete information can be replaced by assumptions and this circumstance is analyzed in this paper in more detail. The management of assumptions is included in an adapted mechatronic design process model and this approach is tested with the application example of a conveyor system. In the conclusion, advantages and disadvantages of assumptions in the design process are discussed. The aims are to make design processes better manageable and to progress faster in the direction of a consistent solution.

1 INTRODUCTION

Mechatronic products provide many advantages such as improved precision, performance, and functionality, but this often results in increasing complexity of the product itself and the related development and design process. This fact is considered, for instance, by Lindemann et al. [LMB09], who discuss complexity for product development and declare that complex systems have a dynamic development process with a lot of changes. To understand complexity in terms of product design, they distinguish between simple, complicated and complex problems. Simple problems are characterized by a small number of parameters and connections, whereas complicated problems possess a lot of parameters with an intensive connectivity. The structure of a complicated problem is stable during a certain time period, whereas complex problems are characterised by high dynamics of change.

It is possible to use design process models for managing complexity in the design process better. Also Clarkson and Eckert [CE05] discuss the increasing complexity of design and argue that the design process is of prime importance for handling such complexity. The enhanced usage of mechatronics in product development frequently increases complexity. As a consequence, design process models have to be adapted accordingly.

The paper is structured in the following way. First, a comprehensive literature research with respect to design process models is performed. The next section describes incomplete and missing information in the design process and proposes an appropriate procedure for its management. In the following, an adapted mechatronic design process model is presented for which the application example of a conveyor system is used for validation. A conclusion and future prospects close this paper.

2 RELATED WORK REGARDING DESIGN PROCESS MODELS

The authors performed a comprehensive literature study and identified a large number of established design process models. Lindemann [L09] proposes the Munich Procedural Model (MPM) which consists of seven elements combined by several network connections. A standard procedure through the network is possible, and flexibility is also shown because of several possibilities to navigate through the design process model. Another well known design framework is the "Systematic approach to the Design of Technical Systems and Products" described in the VDI-guideline 2221 ([VDI2221], [VDI2221e]). This guideline relies on basic investigations by Pahl and Beitz, who developed a systematic approach for engineering design. The latest edition of their influential book [PBF+07] refers, among others, several times to the VDI-guideline 2221 (e.g. general approach to design and stepwise development of a mass product). Apart from that, the VDI-guideline 2206 [VDI2206] is a widespread approach focusing on the "Design methodology for mechatronic systems". This guideline proposes to apply the so called V-model, which is well known from software engineering, to mechatronic systems. After analyzing all requirements, the interdisciplinary solution concept is defined in the system design step on the left side of the V-model. Following up, this interdisciplinary solution concept is partitioned into the discipline-specific solution parts that have to be designed by the discipline-specific development teams. The right branch of the V-model is representing the system integration, a phase in which the assurance of properties is essential. The result of the process, the integrated solution, is evaluated against the requirements. The whole process is accompanied by modelling and model analysis (model based design). After passing this macro cycle, the result can be a laboratory specimen, a prototype, or the final product, depending on the degree of maturity. Eigner et al. [EGZ12] use the V-model and create in their paper an extended model-based approach in virtual product engineering design, whereby the left wing of the V-model is extended with methods from model-based systems engineering (e.g.: modelling and specification, modelling and first simulation, discipline-specific modelling and simulation).

The VDI 2206 guideline describes how to create a system design in principle, but gives only restricted advice to certain details such as intermediate steps and decision points. Follmer et al. [FHP+2011] propose a design process model which can close some of these gaps. It describes a general approach for a simulation-based design process for mechatronic systems based on the VDI-guideline 2221. The input to the design process model is generated from a development scenario. The process model comprises the first six design tasks of the VDI-guideline 2221 such as Requirements Design, Functional Design, Principle Design, Architectural Design, Preliminary Design and Detailed Design. It should be noted that the 7th task of the VDI 2221 guideline is not illustrated in this model. The design tasks include work steps (design steps, design tasks), corresponding work results and "internal" iteration loops inside these design tasks. Furthermore, "external" decision points and connections on system level are shown in [FHP+2011]. Ehrlenspiel et al. [EKL07] confirm the importance of the early phases of product development and describe that they are crucial for the success of the product on the market, because the most critical decisions are made in the early phases of product development. Gericke and Blessing [GB11] discuss the advantages and disadvantages of different process models, especially considering multi-disciplinary approaches. Main aspects in this discussion are differences and commonalities among design approaches.

Our research shows that the literature considered above rarely describes how project staff can work with missing or incomplete information in the design process. In the following, this aspect will be analysed in more detail.

3 INCOMPLETE AND MISSING INFORMATION IN DESIGN PROCESSES

In order to get an overview about the topic of incomplete and missing information in design processes as well as its management, the literature study was extended to this subject. Erkoyuncu et al. [ERS+11] detect that the interest in uncertainty has significantly grown over the past century. Lorenz [L08] describes in his dissertation the handling of strategic uncertainties in integrated product development and concentrates on innovation projects. Suss and Thomson [ST12] model uncertainty in the design process with the goal to reduce product development time. Sadlauer et al. [SZP14] focus on the role of iterations and assumptions in the context of product development. Thunnissen ([T04], [T05]) worked on developing methodologies to reduce the impact of uncertainty.

The studied literature revealed that some aspects of missing or incomplete information are covered to some extent, however, a comprehensive solution how to handle and manage missing or incomplete information in design processes was not found. The present paper is an attempt to include a thorough management of missing and incomplete information into mechatronic design process models.

Especially at the beginning of the design process some lack of information is usually evident, because a lot of aspects are not sufficiently defined in the early phases of design. Another critical aspect in mechatronic design arises from the interfaces between the different disciplines involved for which information is required but might be missing. One possibility to solve this problem is information acquisition. However, the required information is often not available or the involved persons do not have enough time to collect or retrieve it. At the very beginning of design, it is the rule that not all of the required information is available and hence, due to the missing or incomplete information, it is not possible to determine whether a considered concept will fail or survive. An example for that is the determination of the geometrical design space in vehicles in the early phases of design, because it is not possible to know exactly in advance, whether all components will really fit into an assumed space. Furthermore, the evaluation of a concept is also afflicted with uncertainty. It is possible that the early design draft has to be rejected, because certain new information necessitates such a step.

Sometimes it is possible to acquire missing information through research. If missing information cannot be researched, then it makes sense to make assumptions about it. Project staff is usually making a lot of assumptions in their work, but these are frequently not disclosed, not documented and are often made unconsciously. Hence, to the authors' opinion, a conscious management of assumptions including their disclosure and documentation could be a key to improve the management of missing and incomplete information in design processes. Furthermore, assumptions should be tested and verified as soon as possible in the course of the design process. The resulting research question is: "Is it possible to support the design process by a thorough management of missing and incomplete information by replacing such information by conscious, transparent assumptions including their validation and documentation?" If assumptions turn out to be wrong, iterations might be necessary. If assumptions are documented properly, the "entry point" of the iteration is indicated by the point where the assumption has been made. Thus, a consistent solution should be faster approached.

Conscious assumptions can be very useful in a lot of areas in the design process and therefore we include a thorough management of assumptions in an adapted mechatronic design process model.

4 AN ADAPTED MECHATRONIC DESIGN PROCESS MODEL

A mechatronic design process typically involves several disciplines (e.g. mechanical engineering, electrical engineering and information technology including software engineering). The mechatronic design process model illustrated in Figure 1 relates to the "Design process model" of Follmer et al. [FHP+11]. This model provides an overview of a mechatronic design process and consists of six design phases: Requirements Design, Functional Design, Principle Design, Architectural Design, Preliminary Design and Detailed Design (as already mentioned above, the 7th step of the VDI 2221 model is not illustrated in this model).

Figure 1 illustrates an adapted model of the mechatronic design process. The core element in the centre of the model emphasizes on the continuous pursuance, fulfilment, adaptation and documentation of requirements and assumptions. Requirements of stakeholders (including customers, owners, users, operators, legislative bodies etc.) to the product are clarified and specified at the beginning of the process, but – as a rule - they are incomplete and exposed to change during the process. Based on that, it is inevitable, to make assumptions in order to be able to proceed and to come to a result. After that, evaluations and validations of the results of the different design tasks against requirements and assumptions are necessary. Accordingly, "external" decision points are integrated into the design process model. If requirements do not seem to be reachable, "external" iterations might become necessary. Additionally, iterations inside the several design tasks are incorporated in the process model. Such an "internal" iteration is shown in Figure 1, for example, for the functional design task. All other design tasks include the possibility for such "internal" iterations as well. The "main stream" of the process model is highlighted by the broader arrows in Figure 1. Navigation among design tasks is necessary because assumptions and requirements may change dynamically. Several aspects, such as missing information, or requirements that are unreachable for the current solution, may cause iterations.

In case some design tasks strongly depend on each other, the authors propose to combine them. In some cases, Functional Design, Principle Design and Architectural Design are strongly inter-related. For instance, if the geometrical design space is very restricted, these three design tasks might depend strongly on one another because a typical question is: “Which solution principle can be used for this restricted geometrical design space?” Furthermore, the transition between Preliminary Design and Detailed Design might be blurred in some cases; hence, it might also make sense to combine some of these design tasks at least partly.

The multi-disciplinary nature of mechatronic design processes requires an appropriate coordination across the design tasks, phases and disciplines. A lot of information and assumptions are typically processed during the design process by staff members from the different disciplines involved who bring into play specific views on the design problem. Hence, also the corresponding information and assumptions will be related to different disciplines and views. Above all, an interdisciplinary view on the overall system, the product, is indispensable. This distinguished view should be represented very clearly, for instance, by responsible system architects or systems engineers.

Figure 1 should be understood as an integrated design process model that might be “filtered” with respect to different specific views that are not displayed separately in Figure 1.

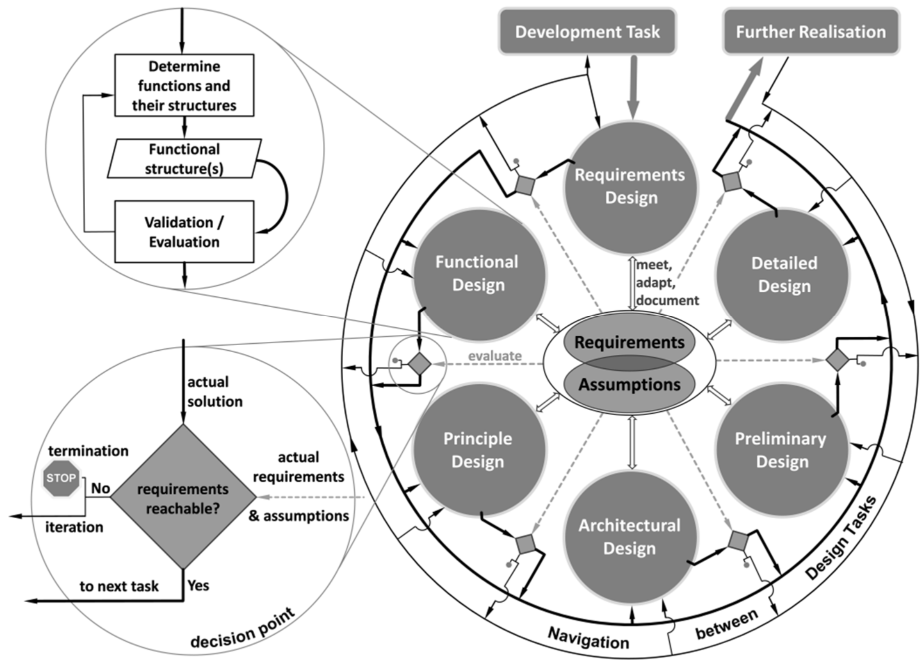

Figure 1: Adapted mechatronic design process model

4.1 The role of assumptions in the adapted mechatronic design process model

In many cases assumptions are necessary to make progress in the design process. Assumptions should be evaluated during the design process as soon as possible, hence, it is important to make them consciously and to document them. The advantage is that the necessity of iterations due to the change of assumptions can be detected with significantly improved accuracy. For instance, in the event that iterations result from a change of conscious and well documented assumptions, the source of such iterations is immediately obvious. Thus it should be possible to navigate more efficiently through the development process and to proceed faster towards a consistent solution.

Moreover, assumptions in the sense of actually adjustable information can be seen as adjusting screws for the solution space that are used to improve the match between solution and requirements. Hence, assumptions enlarge the optimisation potential for the solution. In contrast, confirmed (solid) information in the sense of actually fixed information at the same time is regarded to represent the fixed boundaries (fixed screws) of the solution space. Hence, it is important to be aware of all assumptions made so far during the development process in order to be able to distinguish between adjustable and fixed information and to utilise the full (optimisation) potential for the solution. A prerequisite for documentation and traceability of assumptions is again to make them consciously and, where indicated, to change them consciously.

It should be noted, that the allocation of some piece of information either to the category of assumptions or to the category of confirmed information, may again be seen as an assumption. This allocation should be regarded as temporary or preliminary, because in the course of the design process, it might turn out that some assumptions are wrong or at least inappropriate and thus should be changed. The same can happen with assumptions about allocating information to one of the two categories described above; hence, assumptions may be changed to confirmed information and vice versa.

The proposed treatment of assumptions in the course of product development processes reveals the character of design as a goal oriented play with requirements, assumptions, solution elements, evaluations, and decisions.

It is more the rule than an exception that assumptions have to be made even about requirements, as customers, or even more generally, stakeholders do not provide all requirements; hence, assumptions about requirements may become necessary. As a conclusion, assumptions might be useful also about requirements as the latter have to be complemented and are often changed in the course of the development process. An essential aim, on the other hand, is to minimise the amount of assumptions and to replace them by confirmed information to get a (more) verified basis for the requirements and for all other topics about which assumptions had been made during the design process. This basis of solidified information is the floor that is necessary to specify the final solution.

For complex design processes it is usually not possible to make decisions without assumptions. In the following, it is described, how assumptions are involved in the decision process between the design tasks. The “internal” iteration loops inside each design task should guarantee that its work result, the “actual solution”, seems to be consistent with the actual requirements including all uncertainties (of assumptions and requirements). Thus, every design task is followed by an inquiry: “Are the requirements reachable?” In the face of the uncertainty of available information (assumptions) this inquiry can be formulated more precisely as: “Do the actual requirements seem to be reachable for the actual solution under the actual assumptions?” If the answer is yes (or yes, with high probability), the process continues with the next task. Otherwise, the “internal” iteration loop was not successful, i.e. some inconsistency between the “actual solution” and the actual requirements could not be resolved. Thus an “external” loop becomes necessary, which can include changes of requirements or assumptions, or the project might even be terminated. If an “external” iteration loop is necessary, a return has to be made to a previous step as far as needed, but where is the best entry point for that? If an assumption is to be changed (because it turns out to be wrong or hard to be fulfilled), a conscious disclosure and documentation of all assumptions made so far can help to find the right entry point for this “external” iteration, provided the documentation includes all objects (e.g. solution elements) that are affected by the related assumption. For the “final solution”, all inconsistencies with respect to the “final requirements” and the “final information” have to be resolved.

In the following, the adapted design process model with an integrated assumption management is described and tested by means of the application example of a conveyor system.

5 APPLICATION EXAMPLE – DEVELOPING A CONVEYOR SYSTEM USING THE ADAPTED MECHATRONIC DESIGN PROCESS MODEL

In the following, the approach described in Chapter 4 is to be validated. For this purpose, the adapted mechatronic design process model was validated by means of the application example of a conveyor system, which represents a typical mechatronic system. Conveyor systems are used for a lot of purposes (e.g. transportation, sorting, etc.), and a high number of variants and configurations are available. In this paper, the systematic design of a conveyor system in a factory building is described. For significant, initially missing information, it was necessary to make a lot of assumptions during the development of the conveyor system.

This application example was used to reflect the assumptions that had to be made during this design process in order to become aware of them and to be able to incorporate them into the adapted design process model. Thus the suitability of this model for an appropriate management of assumptions during design processes was validated at least to some extent.

5.1 Development Task

The development task in this specific case is to systematically create a conveyor system in a factory building that already includes a transport lane and an existing facility. Two different kinds of packages start at the entry point and have to be identified and separated at the exit. Furthermore, the transportation has to overcome the existing obstacles in form of the existing facility and the transport lane (see Fig. 2). Requirements of the customer include a good space utilisation and a modular design. Figure 2 illustrates the factory environment and two possible layouts of the conveyor system, such as the longest path (red line) and the shortest path (green line). Additionally, possible standardized modules such as a straight transport unit, corner transfer, ascent unit and descent unit should be used. For this task the adapted mechatronic design process model is applied.

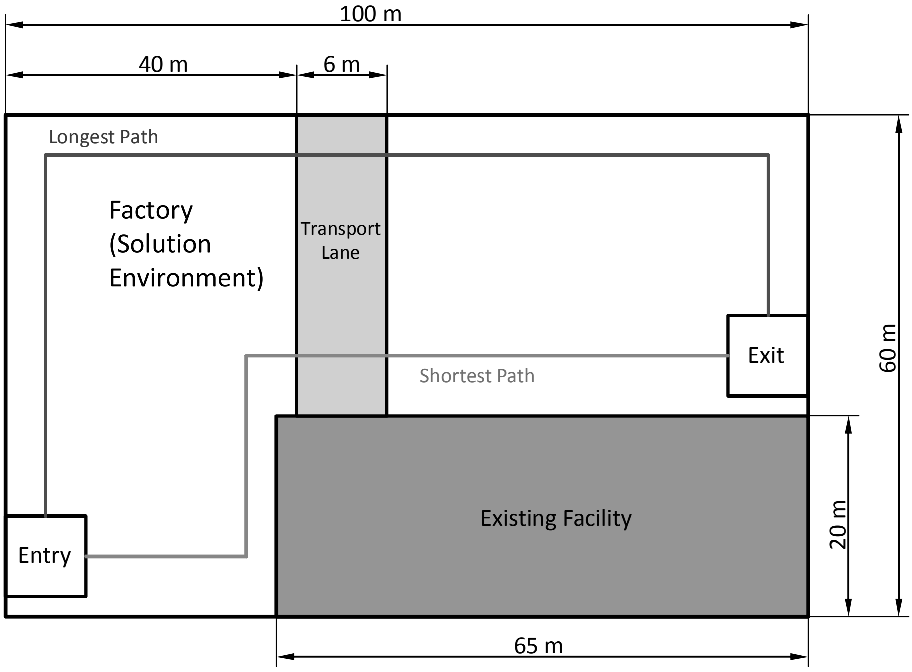

Figure 2: Specification of the conveyor system

5.1.1 Specification

Starting point is a shop floor with given dimensions, an existing facility and transport lane as well as entry and exit section (see Fig. 2). Two different kinds of packages have to be transported on the conveyor system. Possible distinguishing criteria are the different dimensions (Cube: a = 30 cm; Cuboide: a x b x c = 10 cm x 40 cm x 80 cm) and the different weights (Cube: m = 20 kg; Cuboide: m = 15 kg).

In the following, examples of customer requirements are listed (A mix of requirements is assumed):

- Cycle time < 5 minutes
- Good utilisation of space in terms of area consumption, impact on operators, usability of remaining areas etc.
- Low costs in terms of investment costs, operational costs, maintenance costs, cost/benefit ratio etc.
- Identification and sorting of conveyor goods
- Modular design of elements (horizontal unit; ascent; descent; change of direction; sorting)

5.2 Overview

The conveyor system was systematically created with the help of the adapted mechatronic design process model. Figure 3 illustrates an overview of the development process of the conveyor system, and for every step a typical work result is shown. During the design process, a lot of decisions had to be made. Many of them were based on assumptions as some of the desired information was not available and/or could not be retrieved in due time. It was important to become aware of the assumptions that were actually made during the design process and to make them transparent to the involved persons.

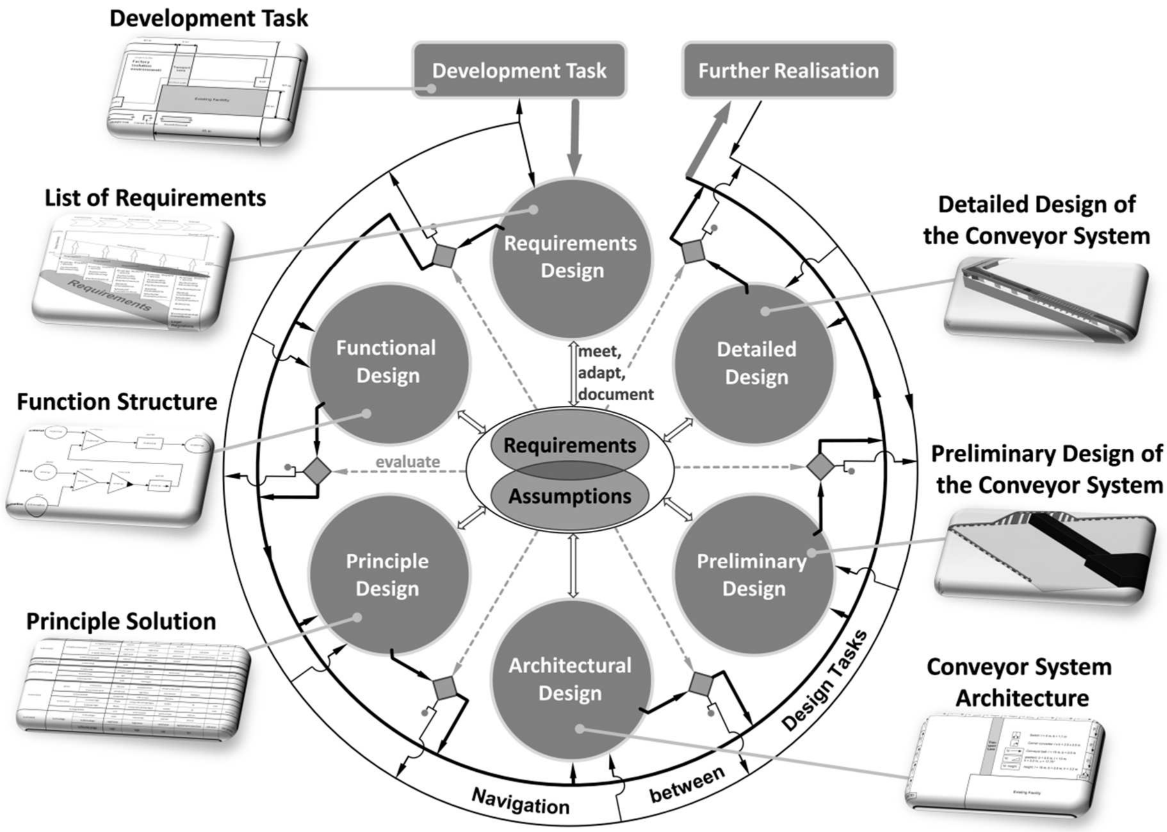

Figure 3: Overview of the design process

At first, the development task was clarified and defined including the acquisition of some missing information. The main result of this step is a list of requirements that is typically incomplete at the beginning of the project. After this step, functions were derived from the requirements. In the design task of principle design, a morphological box was used, where solution principles and their combinations were investigated in dependence of the functions. Afterwards, a principle solution was chosen with the aim to fulfil the requirements. In the design task of architectural design, it was defined, which principle solutions (solution elements) should be combined to the integrated (overall) solution including the interfaces between them. Many different arrangements of the modules in the factory were possible. Finally, the solution of the conveyor system that best fulfils the considered requirements was selected. As soon as the questions “why”, “how”, “what” and “where” were clarified in the first four design tasks, a reasonable preliminary design of a conveyor system could be carried out. In the phase of detailed design, the solution could be confirmed.

5.3 Using conscious assumptions in the design process of the application example

In the following, possible applications of assumptions to the design process are shown. For instance, assumptions can be used in a requirements list, because requirements can also be interpreted as assumptions. For example, a mix of requirements is assumed at the design of a conveyor system.

Generally, it is not possible that all requirements are fulfilled to the optimal extent and so it is necessary to assume a mix and weighting of those requirements that seem to be most useful. To get the requirements, it might be necessary to interview the industrial customer individually or anonymous consumers through a “market research”. It can be assumed that all answers from these interviews are correct. Just as well, it can be assumed that some of the answers are uncertain or even wrong. It makes sense to document such answers as assumptions, because it is possible that customers change their requirements with respect to time or various influences.

In all further design tasks (i.e. Functional Design, Principle Design, Architectural Design, Preliminary Design and Detailed Design) assumptions were necessary to make progress in the design process. For example, a lot of conveyor modules are possible in the Principle Design. First, it was assumed that a roller conveyor is the best principle solution for this case; however, a roller conveyor in combination with a rising conveyor causes troubles, because the package cannot be transported properly. Thus, this assumption was changed, and a conveyor belt was chosen. A further example is the decision of the most appropriate path of the conveyor system in the factory building. We assumed two appropriate transportation paths of the conveyor system in the factory building and evaluated them against several influence factors such as costs, appropriate utilization of the geometrical space and total load of the conveyor system. Also the customer might evaluate the offered possibilities and also this evaluation will be based on assumptions, e.g., his development of sales and the resulting utilisation of his shop floor.

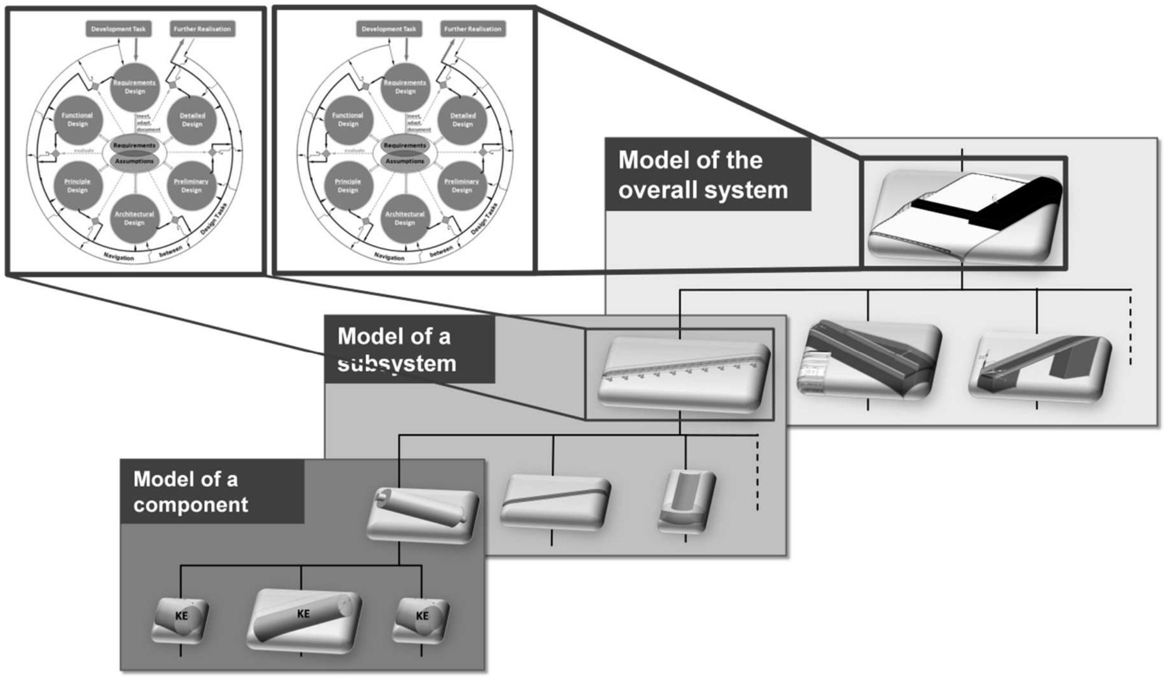

Figure 4: Different hierarchical levels of the conveyor system

In this application example we initially assumed the diameter of the shaft (shown in the bottom left-hand side of Figure 4) and after the creation of the assembly (shown in the top right-hand side of Figure 4) a FEM-calculation was performed. The weight force of the package for the FEM-calculation was calculated based on the above mentioned specification of the conveyor goods. Afterwards, it could be verified whether the shaft was dimensioned correctly. We had created the conveyor system assembly with the help of parameter relations and therefore iterations due to change of conscious assumptions could be performed quickly; for example, if the customer liked to transport other packages and these had a higher weight force. So the diameter and the position of the shafts and the dimension of the conveyor belt in the horizontal conveyor system had to be changed accordingly. It was possible to create these connections in a consistent manner because of making conscious assumptions and their appropriate documentation. These relations could be used and implemented in a CAD model.

6 CONCLUSION AND FURTHER ACTIVITIES

In the following, advantages and disadvantages of conscious assumptions in the design process are discussed.

A disadvantage of making conscious assumptions and their management instead of unconscious assumptions is the amount of accompanying work and the additional time required for this kind of knowledge management, which is primarily in conflict with the existing time pressure of project staff. A further argument against the documentation of assumptions is the lack of convenient software tools for such knowledge management that would be well accepted in the environment of design engineers.

A situation in which the project staff can fully rely on well documented, verified information and need not use any assumptions would be ideal; however, this is not at all typical for the industrial practice. If assumptions are made unconsciously they cannot be documented, hence, problems in later design phases or problems because of staff changes are to be expected.

Thus the questions arises, how missing and incomplete information can be handled. Is it possible to research the required information? If a research of the needed information is possible with an acceptable effort, then this information should typically be used. In this context it makes sense to question the researched information critically whether it is verified information or only an assumption with required verification. This paper claims that replacing of missing or incomplete information by conscious assumptions makes sense in many cases. Assumptions with crucial effects on the design process (e.g. if they hardly can be changed, if they possibly cause expensive iteration loops or affect the whole solution) should be avoided and replaced by verified information. If such information retrieval is too expensive or too time consuming, assumptions are necessary anyhow to make progress in the project. Especially in this case, a careful management of such critical assumptions is necessary including their documentation, monitoring and verification.

The advantage is that conscious and well documented assumptions are traceable and a consistent solution may be approached faster. Furthermore, if such iterations stem from a change of assumptions, then entry points of iterations are indicated by documented assumptions. Moreover, minimization of risks in the design process is probable because of more consistent solutions. So the documentation of assumptions can be an advantage for the whole project. As the costs of changes increase rapidly in the later design phases it makes sense to invest adequate effort in the early phases where the necessity and frequency of making assumptions are highest.

In the present paper, the development and usage of a mechatronic design process model was shown. Key aspects were the use of assumptions to compensate missing and incomplete information. The continuous evaluation and adaptation of requirements and assumptions is incorporated as the core of the adapted mechatronic design process model. Furthermore, a conveyor system was used as a benchmark for this model. As the making of assumptions might be regarded as an essential element of design processes, further effects of conscious and unconscious assumptions will be analysed in future research work.

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