CONCEPT OF MODELLING THE FAILURE MODE EFFECTS ANALYSIS (FMEA) ON THE BASE OF CHARACTERISTICS-PROPERTIES MODELLING (CPM)

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ABSTRACT

This contribution describes the comparison of the Failure-Mode and Effects-Analysis (FMEA) and the Characteristics-Properties Modelling (CPM) in order to define the results of a FMEA (failures, their effects and causes and their rating) which can be modelled by CPM. Additionally, the possibility in order to support the procedure of the FMEA based on existing CPM models is examined. It is shown that most aspects of a System FMEA or design FMEA can be directly modelled by the basic elements of CPM. Due to the fields of application of CPM it is not possible to model the results of Process FMEA which examines for example, manufacturing or assembly processes. For the modelling and support of the organisational aspects of the FMEA, the combination of the functionalities of CPM and of the common project management would be necessary.

Index Terms - FMEA, CPM, Product development

1. INTRODUCTION

Due to free markets, cost pressure and the growing competition of companies the quality of products becomes more and more important. Additionally, new developed products have to fulfil a high number of requirements and functions. Thereby, DIN EN ISO 9000 defines quality as “degree to which a set of inherent characteristics fulfils requirements” [5]. Inherent characteristics represent characteristics which are permanent characteristics of a product or process [5].

Regarding quality, literature shows that an earlier detection and removal of nonconformities and defects cause lesser costs than a removal in later phases of the product development. This is also described by the well-known “rule of ten” presented by Reinhart [14]. Following DIN EN ISO 9000 [5] and DIN EN ISO 3542 [6], nonconformities are described as the “non-fulfilment of a requirement” [5], [6].

According to Werdich [19] one method which can be performed to identify and eliminate the nonconformities / failures of products or processes is the Failure-Mode and Effects-Analysis (FMEA). By its application, failures, their effects as well as their causes will be identified and rated. Based on this, suitable actions can be determined to avoid failure / nonconformity. [19]

Thereby, the development of mechatronic products necessitates a good coordination between the involved developers, because many experts from different domains, each with its special know-how and wording, are involved [18].

Sendler [16] proposes that the main problems are insufficient communication, co-operation and synchronisation of all persons involved (designers). He further states, that there are still challenges realising a continuous data structure of the product models. Furthermore, future generations of tools should enable designers to communicate and co-operate efficiently and furthermore enable developers to get an overview of subsequent or parallel steps of the development processes they are involved in. [16]

Zingel [23] summarises that “a consistent model-based system documentation and representation technique including easily comprehensible traceability, especially between objectives and system architecture, still does not exist”.
Thereby, in the current research project of the research unit 981 (Hybrid Intelligent Design Elements) a new kind of database structured based on the Characteristics-Properties Modelling (CPM) to support the communication and co-operation of the designers will be developed. Due to the importance of the above mentioned quality and coordination, this support must also be able to support preventive quality methods like FMEA.

2. PROBLEM STATEMENT AND GOALS

The CPM by Weber [10], which is used within the research presented in this contribution, represents an approach of design methodology, which, due to its generic character, shall be able to model mechatronic elements as well as the process of their development within a central system model. Thereby, CPM should be able to support the coordination of developers. Literature shows, that there are several extensions of CPM. Weber gives an overview about most of them in [20]. Until now the research regarding CPM focuses on the modelling of functional properties which have to be realised. The modelling of unwanted or disturbing properties has not been investigated in detail.
Crostack et al. [4] show how control systems can be modelled based on CPM as one step towards modelling mechatronic systems. However, a direct examination of the linkage of preventive quality methods like the FMEA and CPM does still not exist. Due to the importance of such preventive methods for the development (realiability, safety) the research questions can be stated as follows:
How can the results of a FMEA be modelled by using the basic elements of CPM (characteristics, properties, relations, external and modelling conditions) and which process steps of a FMEA can be supported by existing CPM models of a product / process?
In order to answer the research question, the following approach is used. At first the basics of FMEA and CPM are analysed. Thereby, the different kinds of FMEA as well as the extensions for CPM are examined in the state of the art. This is followed by a detailed comparison of the elements. Goal of the latter is the identification of elements of a FMEA which can be directly modelled by using CPM. Additionally, necessary extensions for CPM are presented, in order to model the remaining elements. For reviewing this approach, the example of a sandwich element is used. Since Bertsche [1] examined the reliability of mechatronic systems and the use of the FMEA for such systems, it is shown that the procedure of the FMEA is similar to the one for mechanical parts. Hence, the basics of the modelling of FMEA by using CPM can be analysed using a mechanical system.

3. STATE OF THE ART

At first the basics of the Failure-Mode and Effects-Analysis (FMEA) are described followed by a detailed description of the Characteristics-Properties Modelling (CPM). Then a comparison of both can be performed in the following section.

3.1 Failure-Mode and Effects-Analysis (FMEA)

For the avoidance of product failures, there are different methods from the research field of quality management. One of these methods is the FMEA which will be described in detail in the following.
The analytical FMEA was originally developed by the National Aeronautics and Space Administration (NASA) for the Apollo-Program in the 60s. In the 70s, the FMEA was

introduced to the automotive industry resulting in a standard in Germany in 1980. Due to its generic character (FMEA's independence from special industries or products) the FMEA is performed in many branches nowadays. Its main field of application is the reliability analysis for safety-critical systems. [7]

The main goals of the FMEA are the identification, analysis and avoidance of failures, their causes and effects during the development of a product or process [15]. Thereby, these failures shall be removed before the product or process will be released [8]. The FMEA can also be used for the improvement of existing products [15].

Due to the complexity of examined products or processes the method will be performed by a team under the control of a FMEA moderator. This team consists of experts from different departments. For example, for a shaft to be examined by a FMEA the team should consist of members of the development, quality, purchasing and service department as well as of the production planning. [9]

Depending on the literature there are the "System FMEA", "Process System FMEA", "Product System FMEA", "Design FMEA" and further adjusted types of FEMA [15], [13], [9], [8], [7]. By the application of a System FMEA, the connections and interactions of elements in superior systems will be analysed [8]. A Design FMEA focuses on the analysis of components and subsystems and thus of the lowest level of a System FMEA [8]. Thereby, the fulfilment of the requirements will be analysed [9].

In contrast to this, within a Process FMEA for example the development, manufacturing or assembly processes are analysed. Thereby, it will be checked whether or not the manufacturing process is suitable for the manufacturing of the product [9]. However, all kinds of processes can be analysed by a Process FMEA (e.g. service, assembly, recycling or transport processes). The separation between System FMEA and Design FMEA can still be found in literature but is nowadays unusual [7]. Therefore, it will be only distinguished between the System FMEA and the Process FMEA in this contribution.

A strict separation of System FMEA and Process FMEA is not always possible. Process steps are one possible cause for failures or nonconformities within the System FMEA. For example, within the System FMEA it will not be further investigated which causes lead to incorrect processes or why a process step has been skipped for example. These aspects are the main focus of the Process FMEA. Therefore, both kinds of FMEA are connected to each other [7], [9]. For example, one reason for the damaging of a shaft is an incorrect or missing proof of strength which represents a process step. Within the System FMEA this is one cause for damaging the shaft. The causes for the faulty or missing proof of strength will be examined in the Process FMEA.

Although the focus of System and Process FMEA is different, the general procedure of both types of FMEA is similar [15] and will be explained in the following using the example of a System FMEA. Depending on the source of literature, there are slightly different descriptions of how a FMEA is performed. The main aspects including the preparation, the analysis of the system, its functions, potential failures, their rating, the determination of actions and their tracking are part of each description of the FMEA [7], [8], [9], [13], [15], [19]. Due to its detailed description the procedure of Eberhardt [8] will be presented:

1. Preparation
    - Determination of FMEA's content
    - Organisation (team, dates and documents)
    - Preparation of the system structure of the product and the functions of each system element
2. Execution (in a team)
    - Preparation of the analysis

- Determination of failures, their causes and effects
- Capturing of already performed actions to avoid or detect failures (actual state)
- Rating of the failures regarding their importance
- Determination of actions and rating them (target state)

3. Postprocessing
   - Final report including templates
   - Lists of actions and belonging dates
   - Observation of the realisation of the actions

The procedure contains the three main phases preparation, execution and postprocessing.
At first, the execution of each FMEA has to be prepared. For this, the content of the FMEA, including the product or process, the level of detail of the examination and the system boundary, have to be determined [8].
It is essential to clearly define the product or process to be examined. In addition to this, the customer for the FMEA has to be determined, because otherwise different aspects and views for the rating of the failures are mixed and the rating might be corrupted. In this context, customers can be both: end customers who buy the product as well as persons responsible for the following process step (e.g. the manufacturing). [13]
Additionally, a team has to be composed as well as the system structure of the product and the functions of each system element have to be identified [8]. In doing so, all system elements (assembly units and component parts of the product or process steps) and the belonging interactions between them will be identified. In this step the level of examination will be defined, which represents the system elements which have to be analysed as well as their functions will be identified. Based on these functions, the potential failures / nonconformities are identified in the next phase [15].
During the execution phase the prepared structure of the system will be corrected and completed if necessary. Next, the failures / nonconformities, their causes and effects will be determined by the team based on the functions of the system elements to be analysed [8]. Due to the fact that this step requires experience and creativity, well known creativity methods like brainstorming [13], [8] or the checklist from Ishikawa [8] can be used. For the identification of the dependencies between failures, their causes and their effects Werdich [19] proposes the following procedure. At first, for each identified failure, its effects will be identified. These effects are in general failures of the superior system element. Next, for each failure its causes are identified [19]. Eberhardt [8] elaborates that this process of identification of failures, their causes and effects often becomes chaotical and thus they need to be structured and guided by the moderator of the FMEA.
Werdich [19] defines general types of possible failures in order to support the creativity of the FMEA team. These include the complete loss of a function, the partial fulfilment of the function (limited fulfilment or overfullfilment of the function and bad function), a temporary fulfilment of the function and a further unintentional function [19]. The identified failures are connected to each other by a failure tree, thus for each failure its effects and causes can be determined [15]. Additionally, already performed actions to avoid or detect failures / nonconformities, their causes and effects will be determined followed by ranking the failures [8].
The effects of the failure will be rated regarding their severity (S), the failure causes regarding their probability of occurrence (O) and to detect them (E) using the scale from 1 to 10 [15]. Alternatively, the probability to detect the failure or its effects itself can be used, but the detection and avoidance of the causes should be the aim [15]. Based on these three parameters the Risk Priority Number (RPN) will be calculated by the multiplication of all three parameters [15]. Based on this RPN a ranking of the failures is determined. Depending on the

source of literature, there are different criteria to identify the failures which have to be fixed at first. Müller proposes, that every failure whose RPN is greater than a previously defined border (e.g. 125) has to be fixed [13]. In contrast to this [7] and [8] propose the usage of the pareto principle, which means that failures whose RPN belongs to, for example, 15 percent of the greatest RPN have to be fixed [8]. For fixing the critical failures, additional actions will be identified and determined and then rated again (target state) [8].
There are also three different types of actions. There are actions which reduce the severity of the failures effect [15], but this, for example, requires additional component parts and thus can be only performed after consulting the customers [13]. Furthermore, there are actions which lead to a reduction of the probability of failure cause occurrence and actions which increase the chance to detect the cause, the failure itself or its effects [15]. However, actions which avoid the cause of failures have to be preferred [15].
Within the postprocessing phase, a final report including all filled FMEA-templates will be generated [8]. Furthermore, a deadline and persons in charge will be defined for each action. At last, the implementation of the actions and their dates have to be observed [8]. If all actions have been carried out, new ratings of the actual state have to be performed to check whether the actions met the desired success [15].
The processing of FMEA is supported by using form sheets [19]. However, the aim of this contribution is to compare the procedure and results of FMEA with CPM, the existing form sheets and software programs will not be analysed.

Eberhardt [8] identifies different actions to avoid and detect failures [8]:

- Actions for failure avoidance:
    - Technologies (e.g. use of new technologies)
    - Preliminary investigations and tests of the product or change of testing conditions
    - Constructive measures (e.g. containing new components or the change of existing ones)
    - Prototypes, pilot production (e.g. determination that more prototypes are necessary)
    - Experience (e.g. feedback from the end users)
- Actions for failure detection:
    - Results from previous products
    - Analytical or numerical calculations, simulations (e.g. FE-simulation)
    - Experiments for proving different characteristics of system elements or the whole system
    - Tests and experiments of the product
    - Experience (e.g. feedback from the end users)

It is shown, that some actions might influence both, the probability of occurrence as well as the probability to detect failures. After this detailed description of the FMEA, the CPM will be described next in order to identify the results of the FMEA which can be modelled by using CPM.

3.2 Characteristics – Properties Modelling (CPM)

Weber [22] presents a new approach for structuring and modelling products (CPM) and associated development processes (Product Driven Development, PDD). Thereby, according to Weber [20], it was not the goal to develop only one more approach, but also existing

approaches should be combined [20]. One central requirement for the new approach is its ability to combine and implement many existing tools and methods [20].
CPM focuses on the modelling of products based on their characteristics (C_i) and properties. The characteristics define products and can be directly determined by the designers including the products geometry, the arrangement of components, the selected materials and their material characteristics as well as the surface qualities. In contrast to this, the properties describe the product's functions and behaviour and can only be influenced by the product's characteristics. This includes, among others, aspects of appearance, technical functionality of a product, price and weight. [20]
For example, the volume of a cylinder cannot be directly set by designers because the volume is determined by its diameter and height. Latter are characteristics which can be directly set by the designers. The properties are further subdivided into required / target properties (RP_i) and properties representing the actual state (P_i). [20]
Characteristics and properties are connected by relations. Firstly (see Figure 1, left-hand side), there are the steps of the analysis in which the actual properties are determined by characteristics using a set of different relations (R_i). These relations are, for example, experience, formulas, simulations or even experiments. For example, the Hertzian Stress of a gear can be both calculated by analytical formulas or simulated using FE-Simulations.
Secondly (see Figure 1, centre), the characteristics of a product have to be determined within the steps of the synthesis. These steps represent the main activity in product development. Thereby, for these steps another set of relations (R_i^{-1}) is used. These are, for example, association, experience or catalogues. In contrast to the analysis, the determination of the characteristics in the synthesis is not always unambiguous. Resulting from different required properties there might be two contradictory directions for the same characteristic (see Figure 1, flash in the centre). These contradictions have to be solved by the designers. [20]
For the determination of characteristics and properties several external conditions (EC_i) and modelling conditions (MC_i) must be considered [22]. Only by knowing these constraints the validity and value of the relation results can be estimated [21] and thus the results become comprehensible and reproducible. An example for the latter is a linearised formula which can be used only in the direct environment of its set point. An example for an external condition (EC_i) is the restriction of a maximum allowed width of a product, because otherwise it cannot be manufactured in the company. Another example is the specification of the development to tighten a screw using a torque wrench.
Some of the product's numerous properties are less important for customers and therefore do not have to be considered by developers (e.g. appearance of a key connection). Nevertheless, some of these seemingly unimportant properties have to be considered during the development process because they cause disturbances such as loss of power [22].
CPM can also be used for modelling product development processes based on the PDD. In doing so, processes can be seen as a continuous switching between the steps of analysis and synthesis. Therefore, the development process can be modelled as a control loop (see Figure 1, right-hand side). In each step, more characteristics (synthesis step) or properties (analysis step) can be determined or already known ones are determined more precisely using another type of relation. The control loop contains four steps. At first, the determination of product's characteristics based on required properties or, if there was already a run through the control loop, based on the difference between required and actual properties. Next, the actual properties are determined. Then, the differences between actual and required properties are determined followed by the decision if more synthesis and analysis steps are necessary [21].
In each run through the control cycle a different set of relations can be used [20]. For example, in a first analysis step the deflection of a shaft will be calculated using the simplified

model of a beam. In the next analysis step, in which the geometry of the shaft is known, the deflection of the shaft can be calculated by a FE-Simulation with higher accuracy.

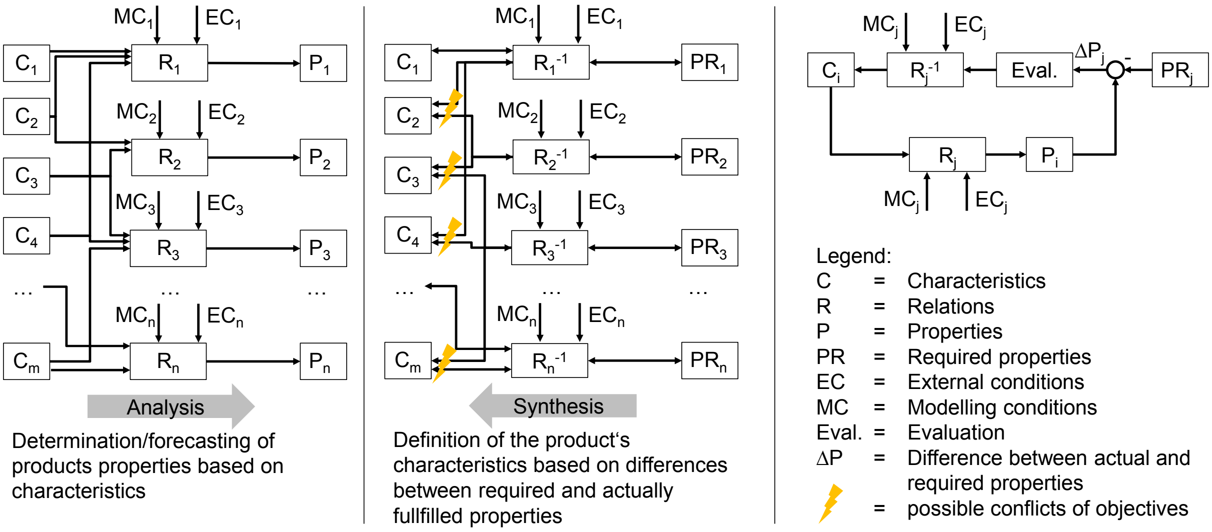

Figure 1: Basic models of analysis and synthesis within the CPM presented in [4] in accordance to Vajna [17] and the general control loop of PDD according to Weber [21]

From CPM's point of view the above mentioned definition of quality is described by the degree to which a set of defined target properties is fulfilled and of nonconformities as the non-existence or non-fulfilment of target properties.

There are some extensions to CPM (e.g. usage and definition of solution patterns, the Change Impact Risk Analysis (CIRA), the usage of matrix based tools) which are not all presented here. Weber gives an overview of them in [20].

The aim of CIRA is to support the process of analysing and rating the effects of product changes. Thereby, an early estimation of the impacts, risks and costs of product changes shall be made possible. For this, CIRA implements the CPM for the synthetisation of different possible solutions and the rating concept from the FMEA in order to determine and document the strengths and weaknesses of each solution. Thereby, Köhlers approach necessitates an existing CPM-model of the product which also has to be evaluated. [2], [3]

Although Köhler uses different aspects of the FMEA, the main aspect, in order to identify failures / nonconformities, their causes and effects is not implemented. He only uses the rating concept of the FMEA. In summary, the state of the art shows that a direct connection of FMEA and CPM has not been examined in detail so far.

4. COMPARISON OF FMEA AND CPM

Based on the state of the art concerning FMEA and CPM, a comparison of both can be performed to identify the elements of FMEA which can be directly modelled by using CPM and which aspects need a further detailed analysis. In a first step, the impact of the FMEA on the development process from the CPM's point of view is examined. Based on this, the FMEA and its steps will be analysed.

The results of the FMEA do not only influence individual properties or relations, but furthermore it may become necessary to modify the product or process completely. Based on an existing CPM-model, the FMEA may lead to a new iteration of the PDD-cycle including both synthesis and analysis steps (see Figure 2, left-hand side). Reasons for this can be, for example, new laws resulting in new or changed requirements.

The FMEA itself is an analytical method which is used during the development of products and processes. Resulting from this, it can be modelled by CPM as a relation during the analysis of a product or process (see Figure 2, right-hand side). In this example, the analysed technical system (light grey highlighted, including C_1, $C_{...}$, P_1 and $P_{...}$) consists, among others, of Assembly Unit 1 (grey highlighted, including C_2, C_3, P_2 and P_3) and further, not represented elements. Assembly Unit 1 itself comprises Component 1 (light grey highlighted, including C_4, C_5 and P_4) as well as Assembly Unit 2 (light grey highlighted, C_6, P_5 and P_6). Latter contains, among others, Component 2 (grey highlighted, C_7, C_8, P_7 and P_8). In the example of Figure 2, the failures of Assembly Unit 2, their effects (resulting failures) on Assembly Unit 1 and their causes from the failures of Component 2 are analysed within a FMEA (R_1: FMEA). This general example will be used in the following in order to analyse the connection between FMEA and CPM.

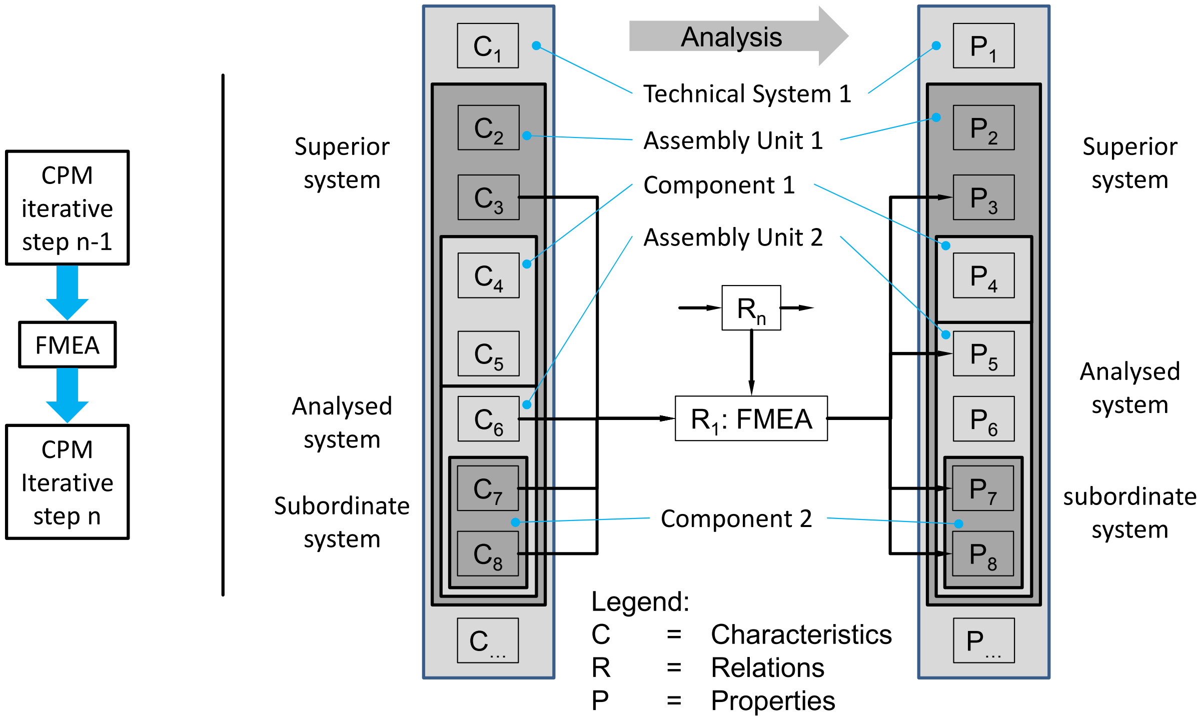

Figure 2: Impacts of FMEA on the development process (left) presented from the view of CPM (left) and FMEA as a relation within the step of analysis in a simplified representation (right)

The potential failures / nonconformities result from the structure of the product or process (e.g. redundancies, system or process elements to detect failures) and their belonging characteristics (e.g. dimensions of a product or selected material). Resulting from this, they can also be comprehended as properties of the system or process elements. The severity of the failure effects, the probability of occurrence and detection of the failure's causes are also properties. They cannot be directly influenced by designers, but rather by, for example, the system or process elements, their belonging characteristics and / or relations. For example, additional tests for detecting failures of manufacturing before the product is released have to be performed. In the case of a mechatronic system, sensors to detect occurring failures during product usage can be implemented.

As already described in Section 3.1, the FMEA comprises several different process steps which might correspond to different relations in CPM. In order to analyse this, the phases of FMEA (preparation, execution and postprocessing) and their including steps will be analysed in detail.

4.1 Preparation phase of FMEA

At first, in the phase of preparation, the system or process to be analysed will be determined. Based on this, the organisational aspects such as the composition of a team and the preparation of documents will be prepared. The final step of the preparation phase includes the preparation of the system structure as well as the identification and assignment of the functions.

Within CPM the relation FMEA is influenced by the characteristics and other functional relations. Based on this, an assignment and modelling of the system or process elements to be analysed by FMEA is possible. The CPM can support the selection of the system to be analysed based on earlier FMEA's modelled by CPM. One possible criterion for the selection of the system or process element to be analysed is the number of important properties of each element. However, this is only one possible criterion for the selection.

In Figure 3 the model still contains the FMEA for the analysis of the assembly unit, as already presented in Figure 2. Because there is still the relation R_1 (FMEA) for Assembly Unit 2 and if it is still in progress or at least based on an actual state of the technical system, another FMEA (relation R_2 FMEA) should focus, for example, on Assembly Unit 1.

By using the basic elements of CPM the acquisition of responsible persons is not intended. However, the constraints of each relation can be modelled in order to allow designers to estimate and evaluate the results of a relation. In case of a FMEA, one constraint is the composition of the FMEA team. If, for example, not all necessary departments are represented, there is a probability that not all potential failures or possible actions are identified. Resulting from this, the composition of the team, the documents, prototypes and models which are used for the FMEA are modelled as external conditions of the relation FMEA (see Figure 3).

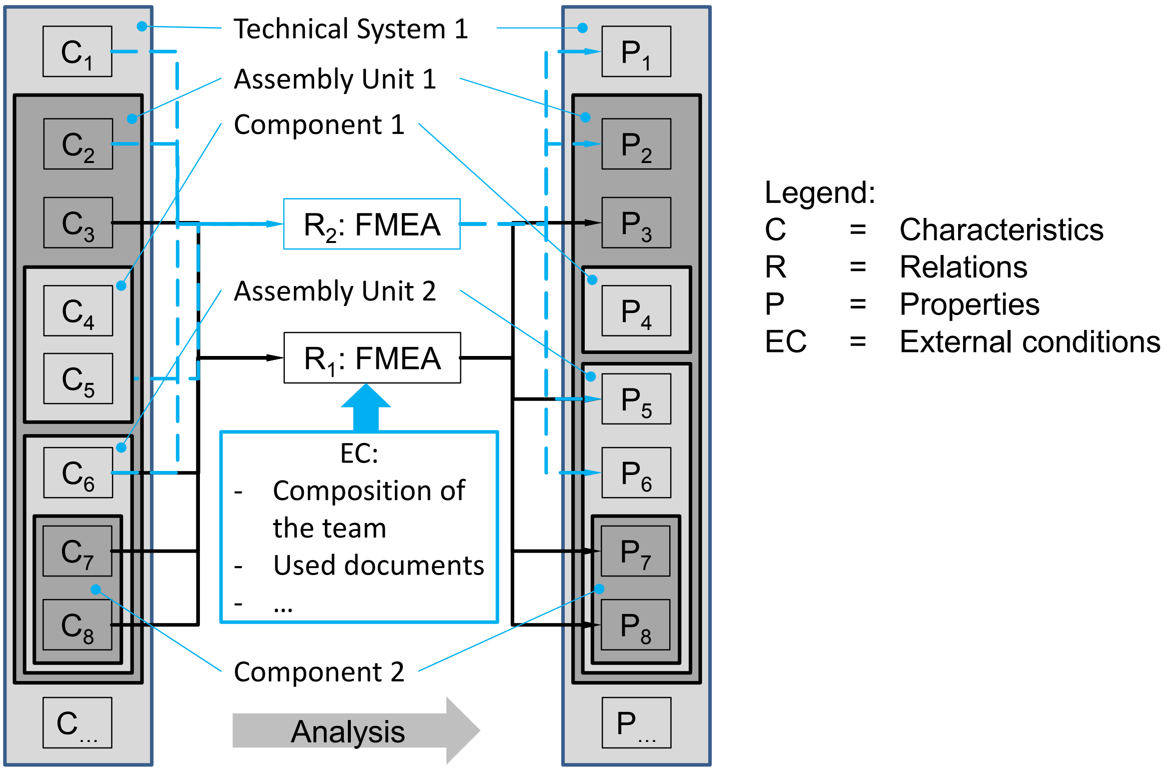

Figure 3: Identification of already performed FMEA for the planning of a new FMEA

The selection of suitable team members can only be supported by already stored information of previous FMEA for the system to be analysed. However, this is not sufficient to select suitable members for the FMEA because, for example, dynamics of human behaviour (e.g. x does not like y) cannot be modelled, thus the instinct of the moderator is still necessary. The determination of dates for the FMEA cannot be supported by CPM, because of its focus on the modelling of products and processes. In order to support this, the functionalities of a project management software (e.g.: MS Project) have to be combined with the functionalities of CPM.

The last step of the preparation phase contains the identification of the structure of the system or process and its functions as well as their assignment to each other. This step is directly be supported by CPM because the structure of the system or process as well as the modelling of the functional relations and properties is one main goal of CPM.

The functions of the system or process element are also directly implemented in the CPM model. However, the functions modelled by CPM are more specific for the analysed system or process. Additionally, the CPM-model contains all possible functional properties which are modelled whether or not they are necessary for the FMEA. Resulting from this, the functional properties and relations which are relevant for the FMEA have to be selected from the multitude of properties and relations which are modelled by CPM. Furthermore, it is necessary to generalise the functions to limit their number. If new necessary functions are defined during the FMEA, these functions and their belonging relations can only be modelled partly by using CPM. For example, the function “keep tea warm” can be realised by a thermal insulation, which can be analysed and rated (relation) concerning its efficiency (property) for example by thermographic surveys. If the FMEA focuses on, for example, the manufacturing process, its functional properties describe the manufacturing process and the suitability of the manufacturing systems. Due to CPM’s focus on the development of products and processes the modelling of functional properties or relations of a manufacturing system is not possible.

4.2 Execution phase of FMEA

The first step in the execution phase contains the completion and correction of the structure of the analysed product or process as well as their determined functions. In contrast to the preparation phase the correction and completion is performed by the whole FMEA team. This step can be supported by using CPM, because the CPM model contains the actual structure as well as the functional relations and properties of the system or process (see Figure 2 and Figure 3).

The next step in the execution phase includes the identification of failures / nonconformities. As already described in Section 3.1, failures of the analysed structure level are caused by the failures of the subordinated system or process element. Thereby, this step of identifying potential failures / nonconformities, their causes and effects can be supported by CPM. The CPM model contains all functional relations and thus, it can be used as a kind of source for potential failures (e.g. by negation of functions and thus of relations). Although this step can be supported by the CPM due to the required creativity and experience, an automated realisation of this step is not possible. The results of this step (failures, causes and effects) can be directly modelled by using CPM (see Figure 4). Thereby, the failures are now described as failures in the CPM model and not as properties as in Figure 3. In the example of Figure 4, in the FMEA R_1 the potential failure F_4 of the Assembly Unit 2 was identified. Additionally, the failures F_2 of Assembly Unit 1 and F_6 and F_7 of the Component 2 were identified. Due to the structure of the product (Assembly Unit 2 is a subordinate system element of Assembly Unit 1 and itself consists of Component 2) the failures of a subordinated element are the causes of the failure of the superior system element. In this case, the failure of Assembly Unit 2 (F_4) is caused by the failures of the subordinate Component 2 (F_6 and F_7). Since Assembly Unit 1 is a subordinate system element of Assembly Unit 2 its failure (F_4) is the cause of the failure of Assembly Unit 1 (F_2) and thus the failure F_2 is the effect of failure F_4.

Furthermore, the example in Figure 4 shows, that the failure cause of a first FMEA (F_4 is one failure cause within R_2) might be a failure of another FMEA (F_4 is failure of R_1). This ambiguity of the assignment between relation and property is contradictory to the basics of CPM. Due to the complex network of failures this ambiguity cannot be solved without multiple implementation of the same aspect (modelling F_4 as failure as well as failure cause). Resulting from this, the number of elements which have to be modelled by CPM will increase significantly resulting in different problems (e.g. keeping the model up to date). Therefore, it is proposed to model the failure causes and effects only as failures which are connected to each other by the FMEA relations and thus are interpreted as failure, cause or effect.
Based on the identified failures / nonconformities the actual state regarding actions to avoid and detect these failures has to be determined. Due to the similarity of the identification of actual actions as well as the definition of further actions, both aspects will be described and analysed together.

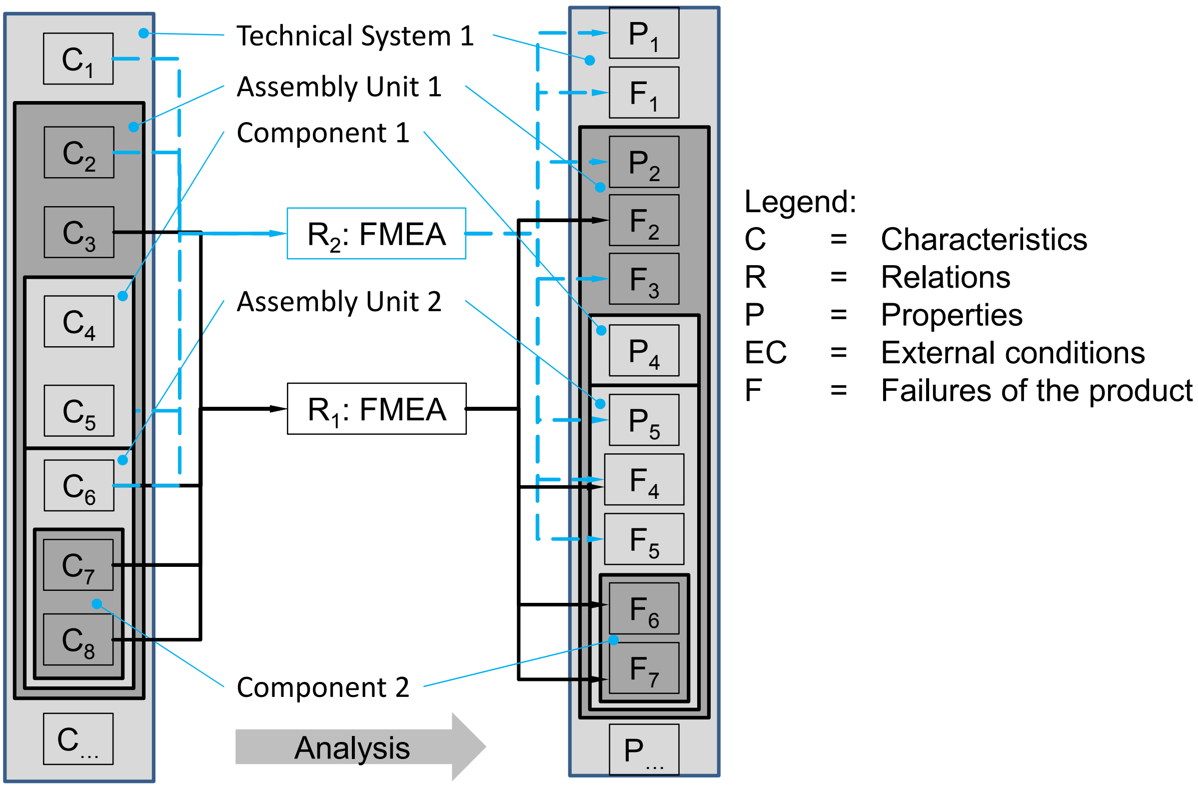

Figure 4: Modelling of failures, their causes and their effects by CPM

Keeping the identified sources for actions to avoid and detect failures / nonconformities as described in Section 3.1 in mind, there are several different aspects to analyse. New technologies can be used during the development (e.g. new working principles, new simulation technologies) or for example in the manufacturing (e.g. new manufacturing technologies). Although Weber presented an approach to model complete X-systems (manufacturing, assembly systems etc.), these aspects have not been analysed in detail and thus cannot be modelled by using the basic elements of CPM. New technologies in the field of development (e.g. working principles) are directly modelled by using characteristics and relations of CPM. For example, switching the technology leads to a switch or addition of a relation.
Another kind of action to avoid failures is the performance of constructive measures (e.g. implementing of new parts or the change of new parts). Reasons for constructive measures like the addition of new components can be the necessity to add a protective device (e.g. out

breaking turbine blades which have to remain inside the turbine housing and thus are not able to damage the hull of an airplane). The dimension of the product (characteristics) itself is also directly modelled by using CPM, but in contrast to the already shown figures the dimensions of the product are determined by relations during the synthesis. The CPM can be used for modelling different iterations of the same product as well as for the modelling of different products. As a result, it is possible to examine previous investigations and tests of a product as a source of possible actions. Already performed measures can be taken from the CPM model because the iterations are also modelled, hence the history of the product is comprehensible. The example of Figure 5 shows a new relation (R_1^{-1}) exemplary for the synthesis by which the characteristic C_6 is influenced.

One type of actions to avoid and detect failures can be calculations, simulations as well as testing of prototypes. Thereby, all three aspects are modelled as relations in the CPM. Hence, existing calculations, simulations, experiments and tests can be directly taken from the actual CPM model. In addition, necessary calculations (e.g. calculation of bearing stresses of a screw connection) are added to the CPM model as relations. In Figure 5 the example shows that the existing unsuitable relation R_3 will be replaced by the relation R_4.

However, not in all cases new calculations of simulations have to be performed. Sometimes only a change of the external or modelling conditions of an existing relation is necessary. For example, it can be necessary to change the used types of elements for a finite element simulation (modelling condition, MC). Another example is the demand to use a torque wrench to mount a screw (external condition, EC). This aspect is also shown in Figure 5 by changing the EC or MC of the new added relation R_4.

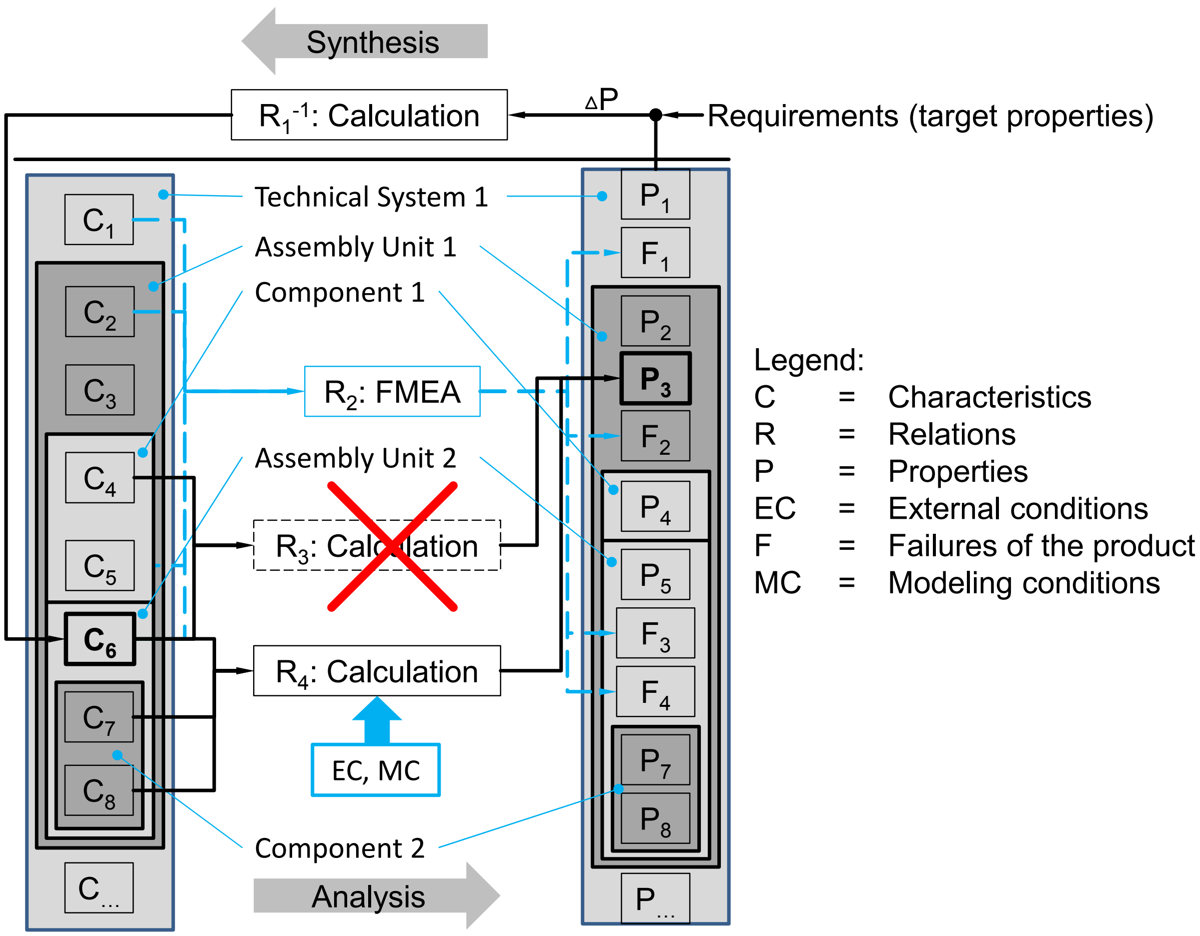

Figure 5: Modelling of actions to avoid or detect failures

Another source of actions is the experience of the FMEA team. The results of, for example, a brainstorming based on designers' experience can be of all previously described types, thus the results can be modelled. However, existing CPM models can only be used as starting point for analogies etc.
Furthermore, the change, addition or deletion of properties is a possible action from the CPM's point of view. However, the properties represent, among others, requirements of the product. Therefore, a change or deletion of a property should be avoided. If it is not possible to avoid it, it should be performed only after a discussion with the customers. New properties can always be added. However, the properties result from relations, which have also to be added to the CPM model.
The next step of the FMEA is the rating of the identified failures / nonconformities based on their severity, the probability of their occurrence and to detect them as already described in Section 3.1. Using the example of Figure 6, the failure F_2 of Assembly Unit 1 lead to the failure effect F_1 (failure of the Technical System). F_2 is caused by the failures of the subordinate system elements (F_3 and F_4 of Assembly Unit 2). Hence, F_1 has to be rated regarding its severity by the FMEA team. The severity of a failure is another property which cannot be directly influenced by the designers. Only by defining actions which will limit the danger resulting from the failures effect it is possible to lower its severity (e.g. addition of protective devices).

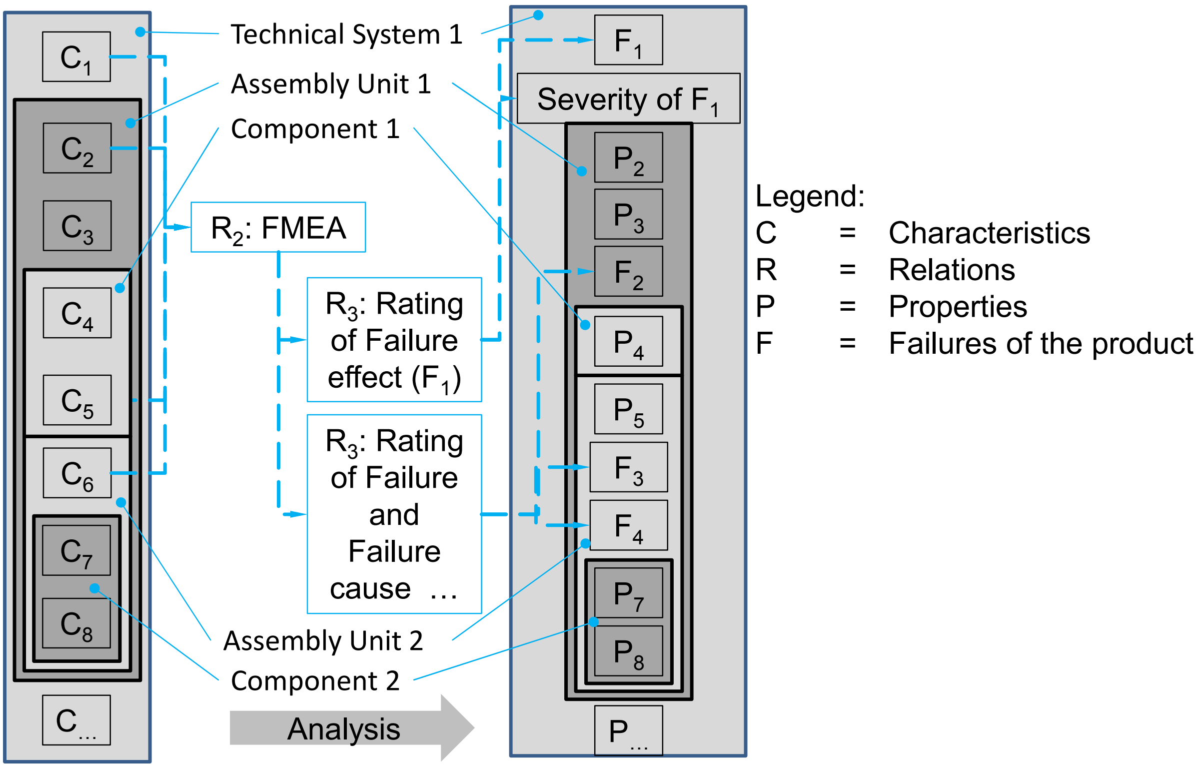

Figure 6: Modelling of rating the failures regarding their severity, probability of occurrence and their probability of detection based on the failure's role in the FMEA (failure, cause or effect)

The causes (F_3 and F_4) have to be rated regarding their probability of their occurrence and to detect them. Both aspects are also properties (not shown in Figure 6). The probability of occurrence can also be influenced by the designers for example based on the principle of redundancy which leads to more system elements fulfilling the same function. The probability to detect the failure's causes can be lowered by, for example, non-destructive testing of the product. This will only raise the chance to find the failure until the product is sold. In case of mechatronic systems, it can be necessary to detect failures during the usage of the system as well, so that the faulty system can be shut down (e.g. if the anti-lock braking system (ABS) of a car detects a failure, for example of the ABS control unit, the ABS will be shut off but furthermore the driver is able to brake the car). The risk priority number of a failure can be modelled by using CPM as another property, because it is only a calculated number from the effects severity, the cause's probability of occurrence and the probability to detect it.

4.3 Postprocessing phase

In general, the postprocessing phase contains process steps which have to be performed by the FMEA-moderator and / or the project manager of the product / process under development. These steps comprise documentation of the FMEA including the complete FMEA templates as well as lists of the identified actions and their belonging dates. The final report is a document summarising the performed procedure as well as the results of the FMEA. The experience of the moderator concerning the procedure of the FMEA as well as the dates for realising the actions cannot be modelled by using CPM. The CPM also cannot support the process of completing the FMEA templates and thus only partly supports the process of completing the final reports of the FMEA. At last, the project manager has to ensure that the defined actions are realised. The observation whether all actions are realised is indirectly supported by CPM, because in the CPM model the performed actions (e.g. new relations) are modelled. To fully support this step, the combination of the functionalities of CPM with the functionalities of a project management software program (e.g. MS Project) would be necessary.

5. APPLICATION SZENARIO

In this section, a first application of modelling the results of a FMEA by CPM is presented. For this purpose, a sandwich element which is under development in the actual research project (DFG research unit 981) is selected. Aim of the research unit 981 is the development of hybrid intelligent design elements (HIKE) which include the functionalities of actuators, sensors, mechanical structures and / or information processing in single design elements. Furthermore, it is the aim to develop a database to support the communication and co-operation of the involved departments. In order to realise this, in a first step, the sandwich element was modelled by using CPM based on workshops with a designer from the Institute of Aircraft Design (IFB) of the University of Stuttgart. Figure 7 presents such a HIKE sandwich element and an excerpt of its system structure. The HIKE sandwich element consists of a mechanical structure which itself comprises two facing skins, a core and glue to combine them, an actuator, a sensor and furthermore the control unit. Both the facing skins and the core consist of fibre and matrix materials. Subsequently, the FMEA will be examined regarding the mechanical structure.

In a first step, the mechanical structure of the sandwich element was modelled by using CPM. Based on the characteristics, relations and properties of the different system elements and their linkage, the CPM model comprises more than 300 elements (characteristics, relations and properties). Due to this complexity only a very small excerpt of the CPM model and the FMEA can be presented in this contribution. Resulting from this, the FMEA to analyse the mechanical structure of the sandwich elements, its failures, their effects on the HIKE sandwich elements and their causes from the facing skins and the core of the sandwich elements are focussed (see Figure 7, highlighted elements of the system structure). After the system structure of the product is determined and the part which shall be examined by a FMEA is selected, the potential failures / nonconformities of the product can be identified.

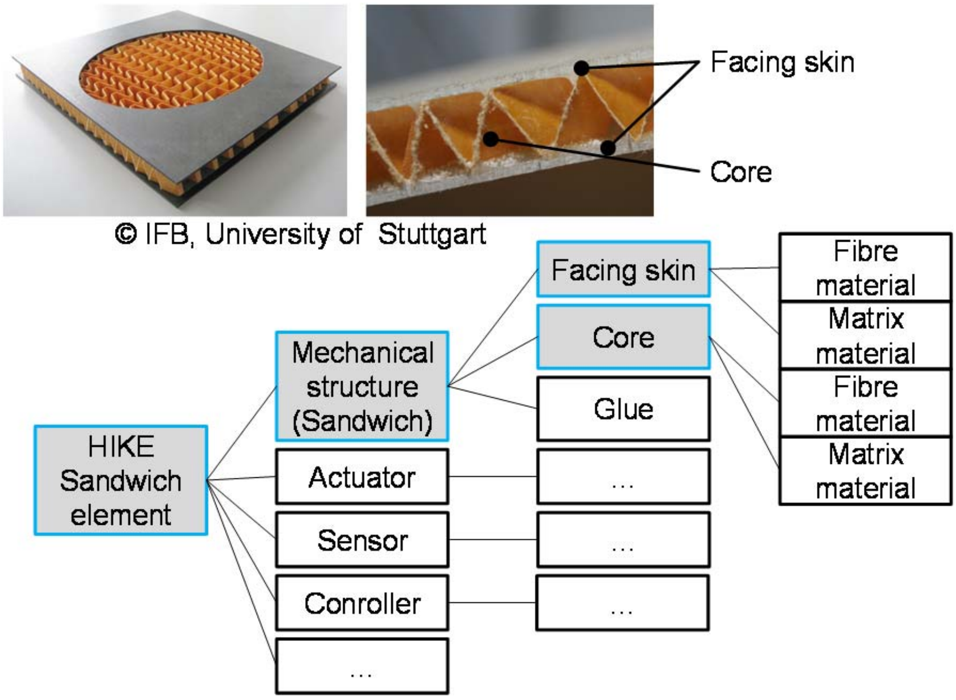

Figure 7: Picture of a sandwich element developed by the Institute of Aircraft Design (IFB) of the university of Stuttgart and an excerpt of its structure

Table 1 gives an overview about some functions and possible failures / nonconformities. For example, the mechanical structure of the sandwich element has the functions to guide external forces to the underground or bordering components (see Table 1). In case of shear forces, they are guided to the core elements which themselves guide the force to the bordering parts. In accordance to [11], potential failures of the mechanical structure of the sandwich element are the damage based on buckling, skin wrinkling, intra cell buckling, local compression or a general overloading. These are only some possible failures which prevent the HIKE sandwich element from taking and guiding external forces.

Table 1: Excerpt of system elements of the sandwich elements, their functions and potential failures

Part	Function(s)	Potential failures / nonconformities
HIKE Sandwich element	- Guide external forces - Absorption of external forces - Compensation of stresses in the facing skins by actuating - …	- Forces are not absorbed - Forces are not lead to other parts - The compensation is not working - Based on the compensation the sandwich element is damaged - …
Mechanical structure of the sandwich element	- Guide the external forces - Absorption external forces - Absorption compensation forces - …	- Damaged by buckling - Damaged by skin wrinkling - Damaged by intra cell buckling - Damaged by local compression - Damaged by overloading - …

Facing skin	- Guiding the shear forces to the core - Absorption external forces - Resistance to bending - Electrical isolation or conductivity - …	- Compressive modulus is too low - Wrong electrical conductivity (too high or too low) - ...
Core	- Absorption external forces - Resistance to shear - …	- Thickness of the folding material is to small - Shear modulus is to low - Compression strength is too low - Cell size is too great - …

In the next step, the cause-effect chains of the failures have to be identified. Which failures of a subordinate element result in which failure of the investigated element leading furthermore to a failure of the superior element? Panel buckling occurs if the core's thickness and shear modulus are not adequate. The sandwich element's ability to resist skin wrinkling depends on the compressive modulus of the facing skin and the core's compression strength. Overloading can be a result of the external force as well as the forces by the actuator which originally shall compensate the external forces. Based on these dependencies, the cause-effect chains of the potential failures can be modelled by CPM (see Figure 8).

In the excerpt of Figure 8 the additional relation FMEA is highlighted. Due to the application field of the sandwich element (for the FMEA it will be assumed that the element is used for a hall roof) the damage of the element has to be strictly prevented. If the functions of the HIKE sandwich element are not fulfilled (no absorption and guiding of external forces, see Figure 8 lower part), in the worst case the hall roof will be destroyed which may lead to serious injuries. Therefore, the severity of the effects of the mechanical structure of the sandwich element have to be rated by 9 or 10. For some of the potential failures, actions are already determined to avoid these failures.

For example, to determine the resistance of the sandwich element against buckling, a FEM-simulation has been carried out. Due to the prototype state of the sandwich element, both shear modulus and core thickness are also checked before the sandwich element is manufactured. Resulting from this, the probability of occurrence and the chance to detect the causes of this failure can both be rated by low numbers (e.g. 3).

In the case of intracell buckling, it will be assumed that instead of a detailed calculation of the sandwich elements resistance against this failure criterion, the designers only count on their experience. Resulting from this, the probability to avoid intracell buckling directly depends on the designer's experience. To become more independent from the experience of single designers and for legal reasons, a good documentation of the development processes is important. Thereby the probability to avoid intra cell buckling will be rated by, for example, 7. Keeping the prototype status in mind, the cell size will be checked whether the specification is fulfilled or not, and thus the probability for the occurrence will again be rated at 3.

Resulting from this, the risk priority number (RPN) of the damage by buckling is 81 (9*3*3) and by intracell buckling is 189 (9*3*7). Thereby, additional actions have to be determined for the failure damaged by intracell buckling. In this case, a detailed calculation / testing of the sandwich element regarding intracell buckling has to be performed.

Furthermore, it was recognized during the FMEA, that the used load scenarios for the determination of the electrical conductivity was not correct. Resulting from this the load scenario was newly defined and the calculations have been corrected.

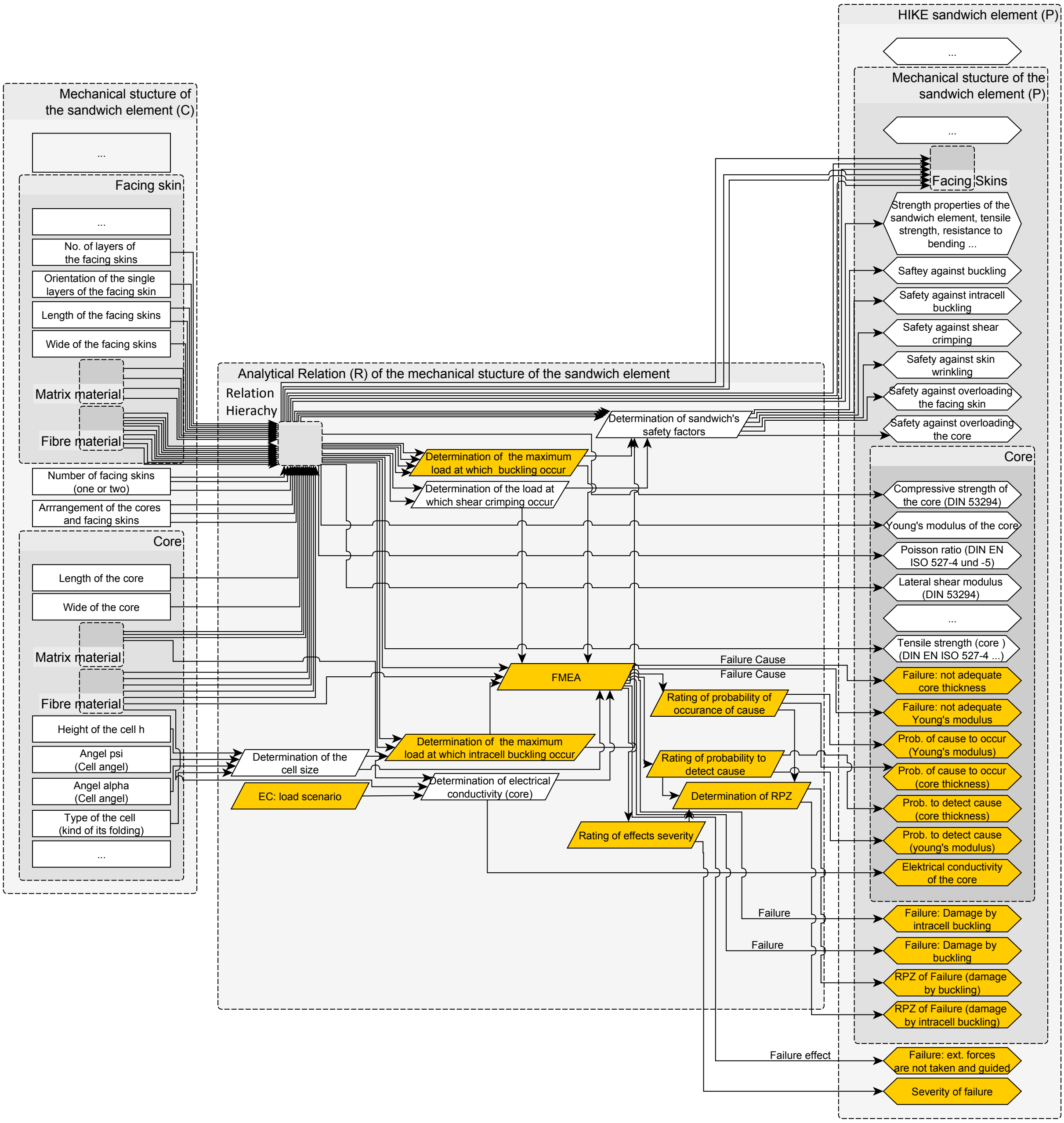

Figure 8: Excerpt of the CPM model of the sandwich element (mechanical structure) including the potential failures / nonconformities as well as actions

6. CRITICAL DISCUSSION OF THE RESULTS

In this section, the presented results are critically discussed. First, it has to be checked if the research question has been answered. The first part of the research question includes the aspect of which results of a FMEA can be modelled by using CPM. In case of a Process FMEA, the results can only be modelled if the analysed process is a development process. In case of manufacturing, assembly or marketing processes only those results can be modelled, which directly influence the development of the product / process. This limitation directly results from the actual application field of CPM. The modelling of, for example, a manufacturing process by using the CPM is still part of actual research.

In contrast to the Process FMEA it was shown that most results of a System FMEA can be modelled by using CPM. Furthermore, the aspect of how to model the identified failures leads either to unambiguous connections between relations and properties or the modelling of the same failure as effect, failure and cause. Resulting from the first mentioned case, a failure can result from different relations (e.g. in one case a failure is the failure of the FMEA, in another case the same failure represents the effect of a failure of a subordinated system or process element). Resulting from the latter, more properties have to be modelled resulting in an increased challenge to keep the CPM model up to date. The organisational aspects of a FMEA (dates, project controlling including observation of actions) cannot be modelled by using CPM. Therefore, the connection of CPM with the functionalities of project management software is necessary. Although many brief examples are given and a simplified case study is presented, an intensive evaluation of the theoretical results has to be carried out in the future. Therefore, the question of how to store the CPM models and thus the results of a FMEA has still to be answered. After that, designers can evaluate the usefulness and practicability of the presented concept. Then, a detailed concept of the connection between CPM and project management software can be developed.

7. SUMMARY AND CONCLUSION

Based on detailed examination of the Failure-Mode and Effects-Analysis (FMEA) and the Characteristics-Properties Modelling (CPM), the results of a FMEA which can be modelled by using CPM are identified. The two different types of FMEA (System FMEA and Process FMEA) are examined. It is shown that most results of the System FMEA can be modelled by using the basic elements of CPM. In the case of a Process FMEA the possibility to model the results directly depends on the type of process which is examined. In the case of a development process, most results can also be modelled by using CPM. The results which affect the development process or the product can be modelled if the analysed process is not a development process (e.g. product is hard to produce and thus its characteristics will be changed). In both cases, only few organisational aspects of a FMEA can be modelled by using CPM. Furthermore, it is examined which process steps of a FMEA can be supported by using CPM and existing CPM models. It is shown that the main aspects of a FMEA (determination of products / process systems structure, function and failures) can be supported by using CPM. Only the organisational aspects of a FMEA cannot be supported by using CPM sufficiently. For this, CPM has to be extended with the functions of project management software. The question of how the functionalities can be combined needs further examinations and concepts. Furthermore, the connection between existing software and for example databases which uses CPM is another aspect which has to be examined.

By keeping the vision of the development of a continuous data structure in order to support the communication and co-operation of the designers, another important research question could be answered. It is shown, that by using CPM not only the required properties of a product can be modelled but also undesired ones. Resulting from this, it is also possible to identify their causes and their connections. Within the research unit 981 a database including the information about the HIKE will be developed. This information base is structured based on the CPM. Possible advantages of such an approach are among others the decreasing numbers of iterations based on obsolete information during the development of a HIKE. Furthermore, the different developers receive the relevant information about HIKE in a processed form, which means in a suitable form (e. g. blockdiagramms for the development of controllers). However, the modelling of products using CPM is very time-consuming. Therefore, the question where the benefit exceeds the necessary effort has still to be answered. This can only be answered based on a detailed and extensive evaluation of the approach and the developed database.

ACKNOWLEDGEMENT

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for its support in the research unit 981 (HIKE).

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