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AN EXPERIMENTAL STUDY ON IMPROVING DEPENDABILITY BY INVERSE FUNCTIONAL MODELLING

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Keywords: dependability, inverse functional modelling, heterogeneous modelling, early design phase

1. Introduction

One prominent ambition of today's designers fuelled by the market is to develop products that do not only fulfil the basic requirements (i.e. functionality) but also advanced customer needs (i.e. availability). At best, a perfectly designed product helps to increase the reputation of the company, adds value to the brand by boosting customer affinity and finally guarantees customer satisfaction. In order to assure this satisfaction, modern companies undertake huge efforts. The design process itself must be balanced between well-known variables and product properties: time, costs, available human resources, product and process quality, etc. One fundamental point that customers demand from today's products is high reliability, as can be seen in recent surveys, e.g. in the automotive sector (see fig. 1, left side [DAT 2011]). In contrast to this clearly stated relevance of reliability, the number of car recalls did increase overall from 1998 up to 2010, now counting a total of 185 car brand recalls (see fig. 1, right side [KBA 2011]). This discrepancy of customer demand to achieved product quality still remains unsolved.

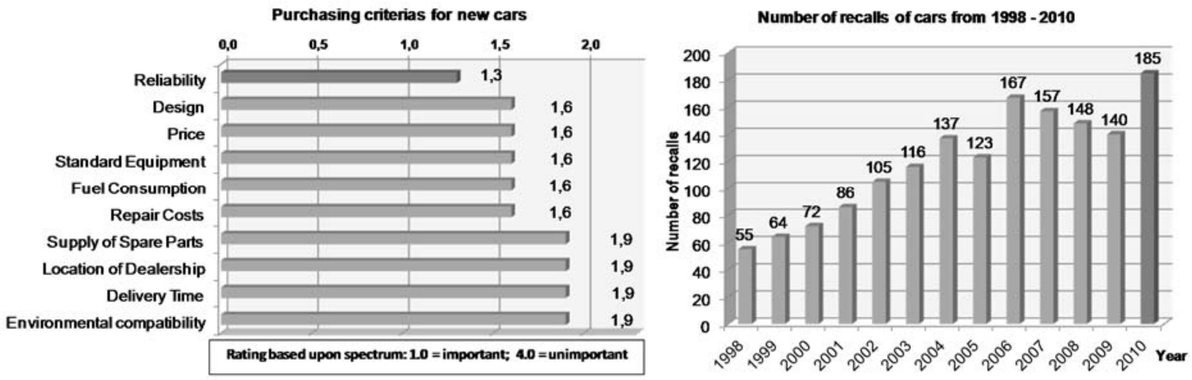

Figure 1. Purchasing criterias for new cars [based on DAT 2011] / recalls [based on KBA 2011]

In addition, the current perception of product quality includes further properties that go along with reliability, like security, safety, availability, maintainability, etc. The term "reliability" is solely understood as a quantitative measure of the time that a system is available until a failure. In order to incorporate the aforementioned, more expanded view, the concept of dependability as described by Laprie is used in this paper [Laprie 2004]. According to Laprie, "[..] dependability is an integrating concept that encompasses the following attributes: availability, reliability, safety, integrity, maintainability."

Looking at the design process with the concept of dependability, it becomes clear that companies nowadays face huge challenges to develop dependable products. Identified barriers during the early phases of the design process include high uncertainty, e.g. due to the use of new technologies and missing experience, increasing product complexity due to the multidomain character of products and insufficient methodical support (see fig. 2, left side). In order to achieve a high level of dependability for a product, it is necessary to prevent as many potential product failures as early on as possible. Although this idea is widespread and known for a long time as the "rule-of-ten" [Bertsche 2004], its realization is still far from complete. What makes it so difficult is that, in early phases, little information about the structure of a product or its possible physical implementation is known. The above mentioned facts also hinder the application of most traditional reliability engineering methods like FMEA (Failure Mode and Effects Analysis [Bertsche 2004]), DRBFM (Design Review Based on Failure Modes [Gamweger 2009]), ETA (Event Tree Analysis [Bertsche 2004]), FTA (Fault Tree Analysis [Bertsche 2004]), RBD (Reliability Block Diagram [Birolini 2007]). Methods like Markov Modelling [Bertsche 2004], Weibull-Analysis [Abernethy 2000], Monte Carlo Simulations [VDI-Richtlinie-4008 1997] or Petri Nets [Schneider 2009] rely very much on quantitative data, which is also not available in early phases of new product development (see fig. 2, right side).

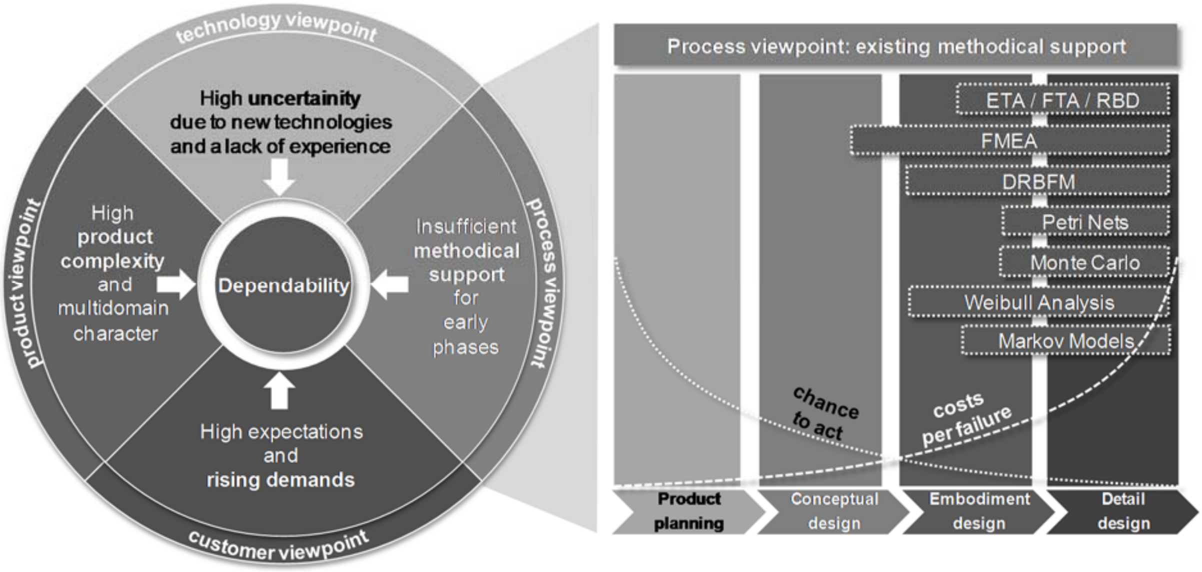

Figure 2. Identified barriers for dependability and existing methodical support

Therefore, the chance to act early on in the design process is hard to realize, making it difficult to reduce the costs per failure (see fig. 2, right side). This is partly due to the insufficient methodical support and due to a lack of ideas how to cope with the sparse information in early phases like conceptualization. The complexity of the design process with its multidisciplinary character is another influencing factor which hinders early failure detection and prevention.

Still, industry as well as academia both state that it is necessary to prevent failures instead of correcting them later on in order to increase product quality, i.e. dependability in the context of this paper. Since uncertainty is strongly associated to missing information and since it has a huge impact on the design process with regards to dependability, a new approach was specifically tailored to improve the current situation of designers. This new approach consists of two methods that are interconnected: heterogeneous concept modelling (HCM) and inverse functional modelling (IFM). The idea of combining both methods is used to support the designer in early phases while modelling his conceptual ideas as well as to already help reduce uncertainties, therefore effectively preventing potential failures [Wendland 2011]. In this paper, an experimental study will be presented with the goal of evaluating the combined approach in order to further improve and adapt it.

2. Research objectives

The main research idea of this contribution is to evaluate the combined approach of HCM and IFM with regards to the early detection of potential failures. Since the combined approach is a completely new methodology coming off a theoretical background, the authors think that it is necessary to conduct an experimental study to successively improve the underlying methods and to adopt it towards practitioners. Therefore, an experimental study has been conducted with n=108 master students in the mechanical engineering department of the University of Bochum. All students had to use the IFM method to find potential failures of a technical system in limited time set. These results were then compared to the usage of the traditional FMEA method in order to evaluate the effectiveness of the new approach. In this process, empirical data was collected by conducting the experiments in fixed settings with a predefined time limit. The basic experimental parameters were recorded and analyzed by the authors. The main objectives with regard to the evaluation were:

- How divergent will be the *overall performance* of the probands in this fixed experiment setting?
- Will it be necessary to divide the probands in clusters based on their performance?
- Which upper and lower limits of *failure detection rates* can be found for the probands?
- On average, *how long* will it take probands *to identify a potential failure* with the use of the IFM vs. the use of FMEA?
- On average, which *quality do the identified failures possess* when found with IFM vs. FMEA method?

3. Fundamentals of the combined approach of HCM and IFM

The need to create models during the design process that represent the current status of the product idea is easy to comprehend. Models represent the reality in a simplified manner, reducing the inherent complexity by omitting some information. They can be used to simulate or validate specific conditions or states of the product. Most models can also be used as a boundary object, i.e. as a means of communication or as a way to present the underlying ideas and principles of the product. In a more simplified approach, models could also provide adequate documentation of the product or its parts, possibly of the design process as well, and allow the establishment of a common comprehension of the product.

One modelling approach that supports the design process for new product development and offers the chance to also support the phase of conceptualization is presented by Pahl and Beitz [Pahl and Beitz 2007]. Here, four different levels of abstraction are applied to separate model elements according to their modelling plane: requirements, functions, active principles and components. By having the designer to pass through all four modelling planes in sequence and formulate their associated elements, a strict procedure is established which helps to systematically create new products. Furthermore, complexity is reduced, since only one level of abstraction at a time is examined. Starting from a very abstract description of the customer demands and the first product functions, the approach offers various levels of concretization up to real components on the least abstract modelling plane. Although this procedural approach might reduce complexity, it imposes a few challenges. Almost all real-world design processes do not follow the predefined track of abstraction described above and most do require some form of iterations. Most humans also tend to rapidly switch their levels of abstraction while solving a problem. This can be seen e.g. when designing a new product from the very beginning, most parts of the product might still be unsettled, but some existing parts might offer a suitable solution for required functions. Following the approach of Pahl and Beitz, the designer would have to refrain his ideas until the corresponding modelling plane is reached. Sudden inspiration and innovative thinking are highly valued characteristics of successful product designers and should not be inhibited by the applied modelling approach.

This is why the Heterogeneous Concept Modelling (HCM) approach was selected to be the basis for the application of IFM in this paper. HCM was first developed by Jansen [Jansen 2006] and extended by Sadek in 2009 to product-service systems. In 2010, two experimental studies were conducted in order to improve the teachability as well as the applicability of the HCM approach [Wendland 2010].

The fundamental axiom of HCM is that the designer must use one modelling plane instead of four different planes. By dissolving the traditional four design phases, it is possible to use model elements with a varying level of abstraction on this single heterogeneous modelling plane (see fig. 3, left side). Therefore, requirements, functions, active principles and components can intuitively be used and interconnected to better represent the current product concept. Users of the HCM approach can easily get an overview of the complete product concept and thereby build up a consistent comprehension without having to switch between different levels of abstraction. This approach allows a successive problem solving, since it is able to reflect the aforementioned human behaviour without inhibiting creativity. Furthermore, it does not restrain the designer to a specific procedural setup or level of abstraction, making it flexible, which should prove useful in real-world applications. A more detailed description of HCM is available in [Jansen 2006].

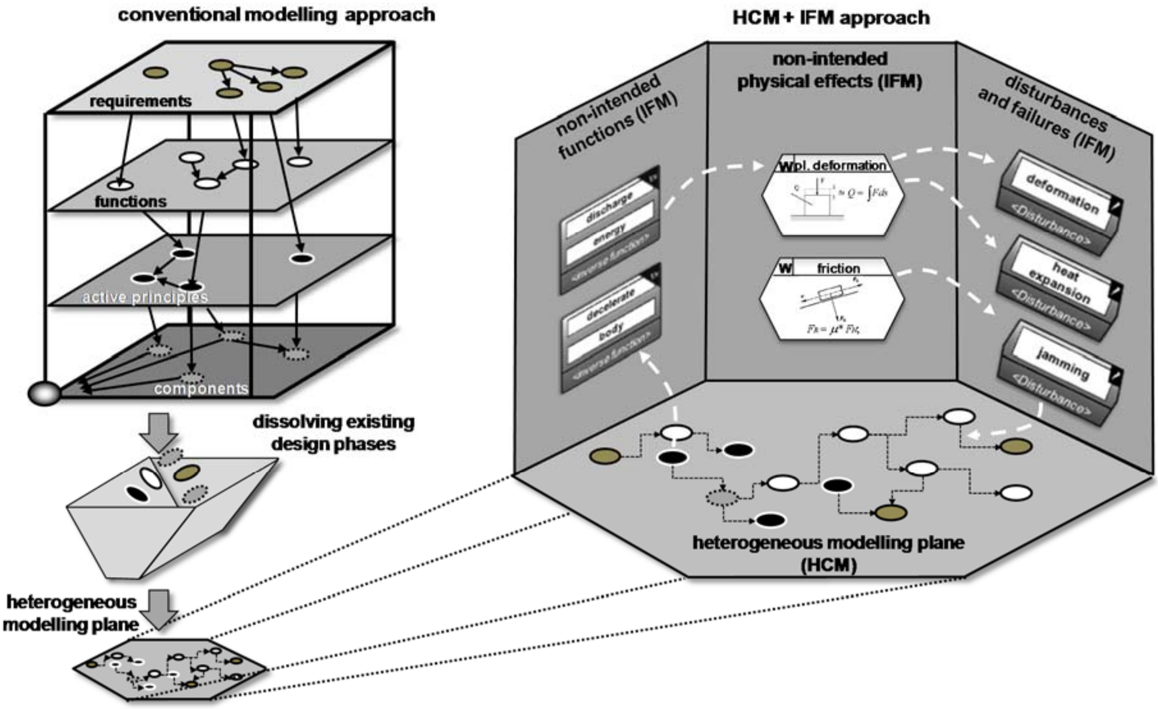

Figure 3. Origin of the combined approach of HCM + IFM

Building upon this basis of HCM, the inverse functional modelling is integrated to form the combined approach (see fig. 3, right side). The main goal of the IFM is to reduce uncertainty in order to identify potential failure modes and to improve the overall dependability of the product concept. To allow the application of IFM during conceptualization, it utilizes the most basic level of modelling, the functional description. Uncertainty in a product concept can cause non-intended behaviour of the designed product, so it needs to be reduced. Therefore, IFM focuses on the non-intended functions and physical effects, because they possess the highest risk of negatively influencing the systems' dependability.

As a starting point for the IFM, the functional description of the product concept is examined. For explanation purposes, just one function is chosen here. In an early design stage, a typical technical function is composed of a verb (operator) and noun (operand), e.g. "accelerate body" (see fig. 4). Following the procedure of the IFM, the function is inverted at first. This is done by inverting the verb, resulting in the inverted function "decelerate body". Now, the inverted function does describe the non-intended behaviour of the system on a very high level of abstraction. To further interpret this inverted function, it is necessary to switch to the physical description layer and search for physical effects that could realize the non-intended function. The intended function "accelerate body" could be realized by many effects, e.g. by "Lorentz Force", which could also result in an active principle of an "electric motor" (see fig. 4, left side). The non-intended function "decelerate body" also features possible effects for realization, e.g. “inertia”, “adhesion” or “friction” (see fig. 4, right side). These effects can be found by browsing effect catalogues, e.g. on the web or provided by Lindemann [Lindemann 2008]. By correlating the intended and non-intended physical effects / active principles, potential disturbances can be identified. In case of the previous example, the following potential disturbances were identified: stalling, splicing, jamming (see fig 4. bottom left side). By connecting these potential disturbances to the intended active priniciple, valuable information about potential failures can be represented in the conceptual model.

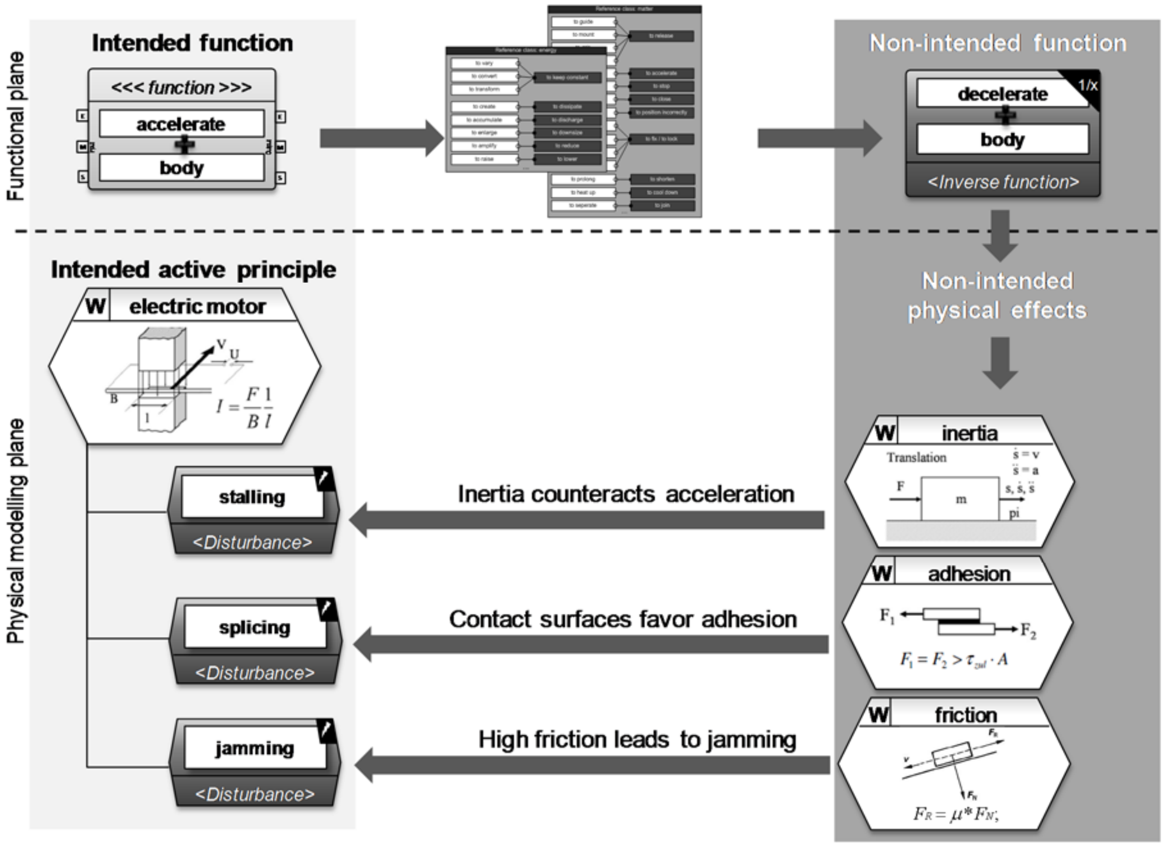

Figure 4. Procedural approach of the Inverse Functional Modelling (IFM)

Future users of this model will directly benefit from the incorporated dependability information and will be able to quickly get an overview. By including this information directly as model elements, no information will be lost when transferring or re-using the model at a later time, as it usually happens when product models and dependability information are kept separated. The identified non-intended functions and disturbances can also be used as a starting point for the FMEA method and can help novice designers to pre-fillout the FMEA sheet. Therefore, by using IFM it is possible to specifically reduce uncertainty in early design stages and identify potential non-intended functions and effects, which would negatively influence the products’ dependability.

4. Basic design of the experimental study

In this paragraph, the basic design of the experimental study will be described, including the fundamental idea of the experiment setup, its procedure, population and recorded parameters. As stated before, the goal of the experimental study is to evaluate the new method IFM, which helps to reduce uncertainty in early stages and thereby increasing a products’ dependability. In order to be able to compare it to traditional approaches, the FMEA method was chosen and integrated in the experiment. This study needs to be understood as a preliminary descriptive study in order to answer the research questions formulated in paragraph two. The experiment population amounts to n=108 master students of the mechanical engineering department. All 108 students were trained beforehand in terms of mandatory class exercises regarding the application of FMEA and IFM, thereby trying to accomplish a common precognition of the probands. Both methods were to be applied to the technical system of a geared fuel pump, which was modelled beforehand by the authors as a heterogeneous concept model (see fig. 5). In addition, the probands were also given a draft with all necessary active principles in order to fully understand the functionality of the fuel pump.

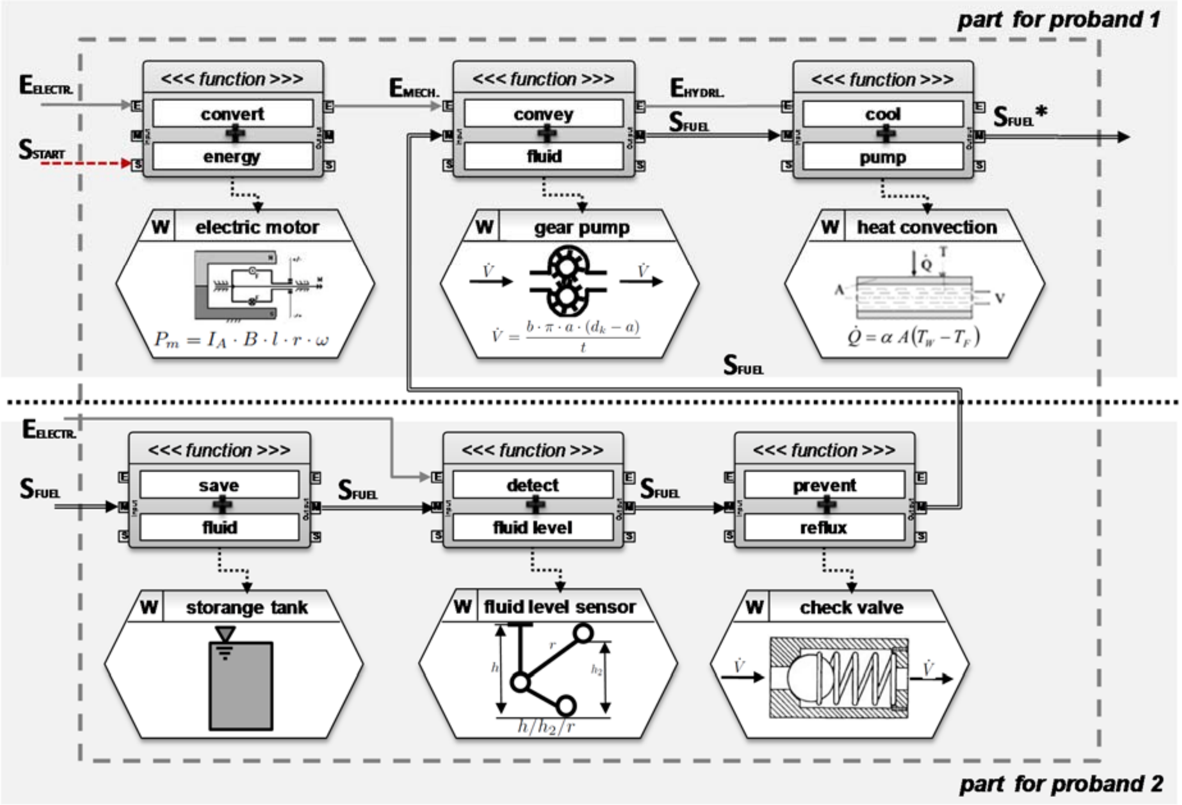

Figure 5. Heterogeneous concept model of the geared fuel pump

The overall time frame of the experiment consisted of 60 minutes, divided into two blocks of 30 min each (see fig. 6). In the first block, the probands had to conduct a typical FMEA for the entire fuel pump, trying to find as many potential failures as possible with the available information and a simple FMEA sheet. In the second block, the probands then had to individually use the IFM method for 30 minutes on a selected part of the technical system. Again, they had to try to find as many potential failure modes and disturbances as before, but now by applying the IFM procedure. This means that they first had to invert all the functions, find disturbances and then interpret them. To aid in identifying non-intended effects, a catalog of possible disturbances was prepared by the authors and given to the probands for the IFM part of the experiment. Prior and closing to the experiment, questionnaires were handed out to check the perception or possible changes thereof for each proband and the applied methods.

The conducted experiments were arranged in groups of two probands each, resulting in a total of 54 groups. Each group had to use the FMEA in the first 30min-block, working together as a team on the complete heterogeneous concept model. For the second 30min-block of the IFM, the group split up and each proband had to apply the IFM method on his own. Therefore, the model was split into two separate parts, one for each proband (see fig. 5, top-part proband #1, bottom-part proband #2). During both blocks, the following parameters were recorded: number of identified overall failures, failure mode, failure cause, time when each failure was found, quality of the failure (rated by a self-assigned risk priority number RPN). This procedure was chosen to allow for later analysis of the authors' team. Figure 6 summarizes the experimental procedure.

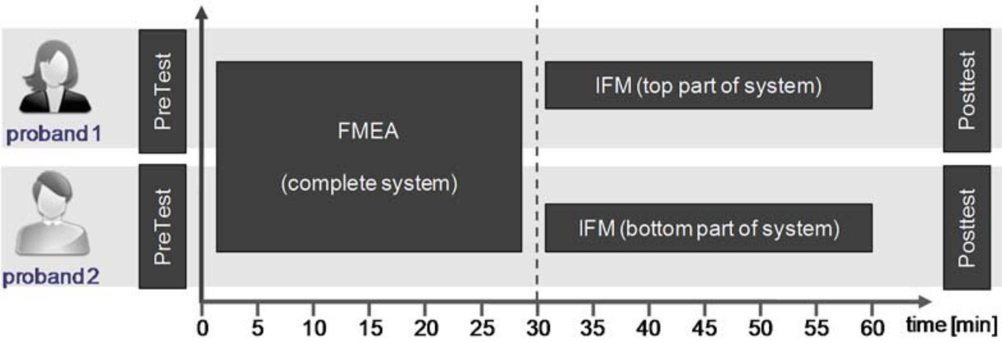

Figure 6. Complete experimental procedure for a group of probands

5. Results and discussion

All 108 experiments were analyzed by the authors' team and all extracted data with regards to the number of overall identified failures, time and risk priority numbers was composed in an excel sheet for further work. Regarding the first research question, the **overall performance** of the probands did vary drastically in the conducted experiments, although the setting was fixed (experiment time was set to 60 minutes, precognition was assimilated, no external support allowed, same technical system and material for all probands). As can be seen on the left side in figure 7, which shows a representative excerpt of the analysis of 10 groups, results varied from the upper performance limit of roughly 150 seconds per failure to the lowest performance level of ca. 277 seconds per failure. To find these limits, compensating curves were calculated for the best and the worst proband results. This difference in performance can partly be explained by different intrinsic motivations of the probands, which also reflects the natural dispersion of human abilities. It becomes clear that the usage of the IFM method cannot circumvent a lack of motivation or skills of the designer.

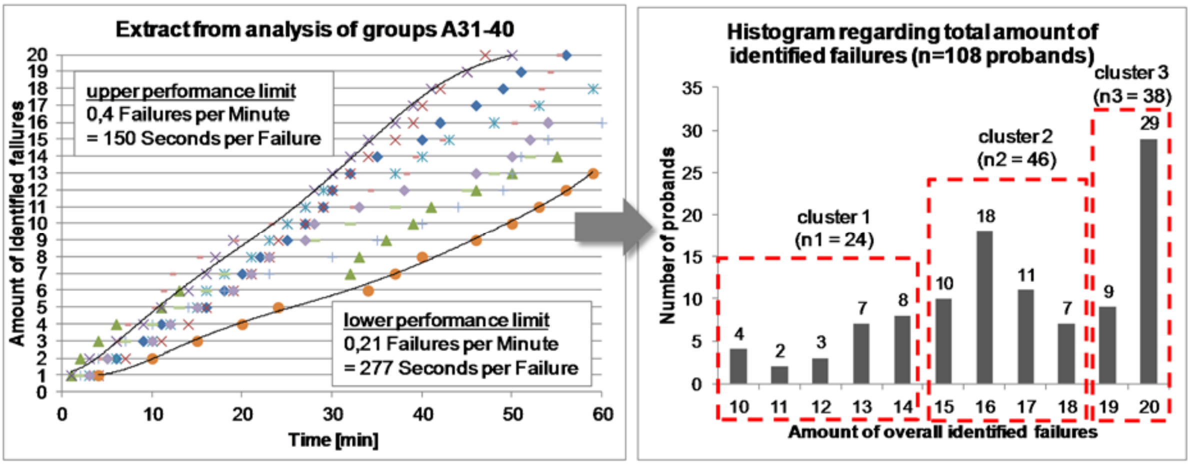

Figure 7. Left – performance limits of probands / Right – histogram for identified failures

This emerging disparity also shows that it is necessary to build clusters of the proband groups, based upon their performance, in order to be able to draw valid conclusions. This process can be seen on the right side of figure 7. Here, a histogram shows the distribution of the total amount of identified failures on the horizontal axis against the number of probands for each category on the vertical axis. Since the performance of the probands did vary severely, three clusters were built to accommodate groups of similar performance. The first cluster, which is representing the lower performance boundary with a total of 24 probands, includes all groups that found 10 up to 14 potential failures. The second cluster includes 46 probands, who identified 15-18 potential failures. The third cluster contains 38 probands, each identifying 19 or 20 potential failures and therefore resembling the upper performance limit (see fig. 7, right side). Without this clustering, the arithmetic average applied on all groups would not allow a dedicated evaluation, since the data will be smoothed too much. With respect to this clustering, the research questions can be answered in detail.

Regarding the **average number of identified potential failures** (see fig. 8, part 1a) for each method, it can be seen that the new IFM method does not differ much from the standard FMEA. While cluster 1 and 2 almost feature identical amounts of identified failures for both methods, cluster 3 seems to produce more identified failures with the FMEA (10.84 instead of 9.0 for IFM). This could be explained by the idea that the strict procedural approach of the IFM seems to help the novice designers more than the experienced engineers of cluster 3 (which resembles the high-performance groups). What is quite remarkable though is that the standard deviation on the amount of failures is far less for the IFM than for the FMEA (see fig. 8, part 1b), which means that the IFM method allows to generate more reproducible results.

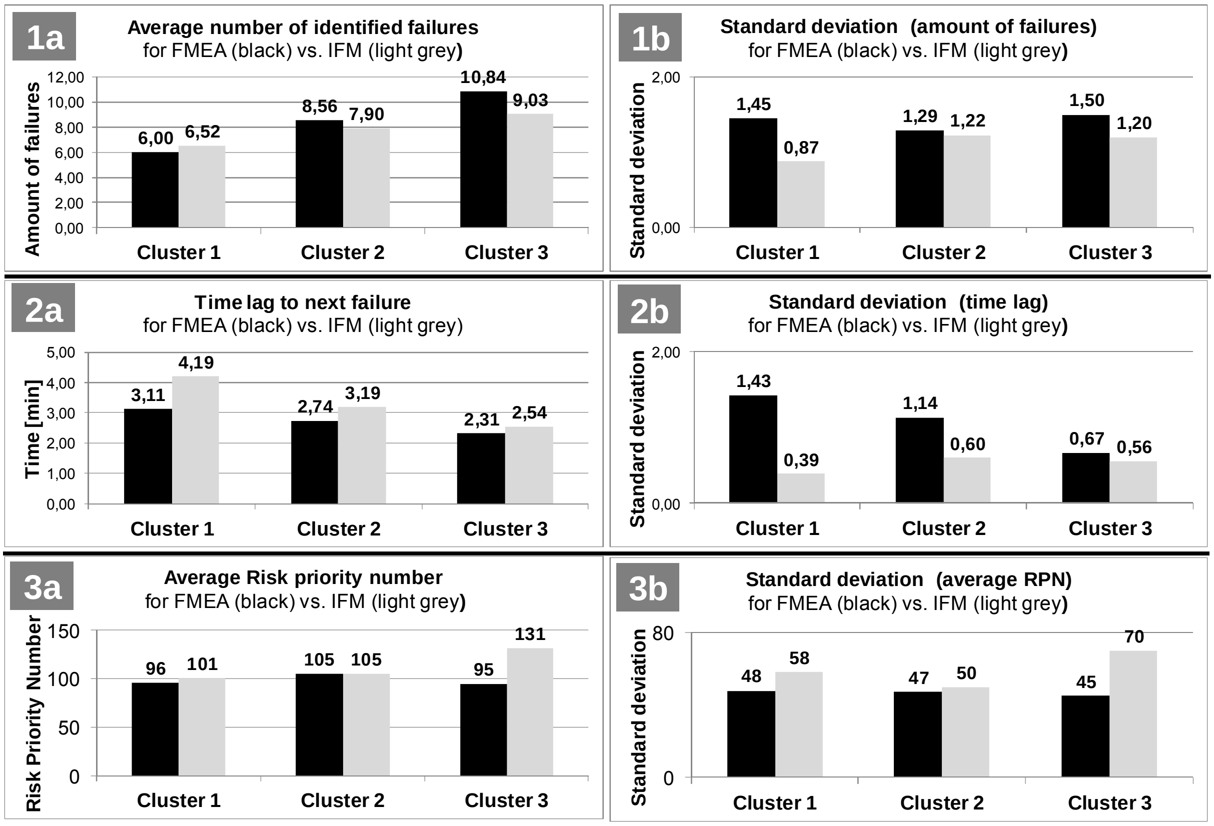

Figure 8. Results of analysis of the experimental data for all clusters

Regarding the **average time lag to the next failures** (see fig. 8, part 2a) for each method, it is shown that the IFM takes a little longer for all three clusters until the next failure is identified. This is especially true for the first cluster, with a difference of almost one minute compared to the FMEA time lag. Towards the more performance-oriented cluster 3, this disadvantage is diminishing, but still in favour of the FMEA. This prospect is changed when considering the standard deviation on the time lags (see fig. 8, part 2b). Regarding the time lags, it becomes obvious that the results of the IFM are produced in a very consistent manner, with very little deviation. In contrast, the deviation of the FMEA results is far greater and seems to mimic the creative, but mostly chaotic process of brainstorming. By using a procedural approach and offering a disturbance catalogue as help, the IFM supports systematic failure detection. This advantage of the IFM seems to lose a bit of effect for cluster 3, which can be easily explained, as experienced users do not benefit from a strong methodical backbone as much as novices might do.

Regarding the **average risk priority number** (see fig. 8, part 3a) for each method, it can be observed that both approaches, i.e. the FMEA as well as the IFM, offer roughly the same amount of quality when it comes to identified failures. Even though the risk priority numbers are assigned by the probands and this is a very subjective process, the standard deviation shows that the IFM and the FMEA are handled in the same ways, which justifies the comparison of these results. Since the risk priority number is calculated by multiplying the three figures RPN = severity * occurance * detection, a slight variation in one of those values produces a great offset of the overall RPN. In this context, a standard deviation of RPN=50 is quite acceptable and still assumed as a suitable result.

6. Conclusion and outlook

The conducted experiments have shown that the new combined approach of HCM and IFM does offer a distinctive benefit when applied by novices or intermediate-level engineers for increasing the dependability of a product concept. For experienced engineers or practitioners with years of training, this advantage is diminishing, since they can administer the traditional brainstorming character of existing methods like the FMEA in an appropriate way. Results have shown that slightly more failures were identified on average with the FMEA, but the IFM does produce very consistent results with regards to required identification time and quality measured by RPN while offering almost the same failure detection rate. Due to its systematic procedure and its support (e.g. disturbance catalogue), the IFM allows novice designers to identify potential failures in the early design phases in a more repeatable and consistent manner. The underlying modelling approach HCM did prove its use for displaying complex interdependencies of model elements as well as to provide the right amount of information in early phases to apply the IFM method. Probands did state in questionnaires that the usage of the IFM increased their understanding of the system as well as that it proved to be of valuable help for identifying yet unknown, but potential failures and disturbances of the system.

Further research is needed to improve the IFM in various areas. First, it is necessary to conduct the IFM experiments with an industrial expert group to verify the conclusions of cluster 3 in a real-world application. In addition, by implementing the feedback of such experts with regards to dependability, it should be possible to further optimise the procedural approach of the IFM. Furthermore, it should be feasible to generate a methodical tool that allows a more easy conversion of an intended function to a non-intended function, e.g. by means of a morphology with predefined technical verbs. Moreover, by building a database with common non-intended functions which are directly linked to the most probable disturbances that occurred in older designs, a reuse of dependability knowledge is achievable. Overall, the IFM method does offer huge potential that should also be used in industrial applications.

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