1st International Symposium on Robust Design
København, DK
14th-15th of August 2014

An approach to identifying the ideal time to perform an FMEA during the product development process

J. Würtenberger, H. Kloberdanz
pmd, Technische Universität Darmstadt

Keywords: level of information, Information-Quality Framework, FMEA

Abstract

The Failure Mode and Effect Analysis (FMEA) is one way to preventatively identify failures. In it, failures and their risks to the customer are analysed and valuated in order to define mitigation strategies for minimization or avoidance. Depending on this purpose, a division into functional, design and process FMEA is mentioned in literature. If the FMEA is used as early as possible during the product development process, the usable level of information is very low. It grows during the product development process and is understood as all available information, with different degrees of concretisations, according to an instant in time. It can be suggested that the available level of information influences the FMEA results as well as the point of time to perform. In order to identify an ideal point of time, a three-step methodology is considered.

First, the level of information is systematized by using product and process models. Subsequently, the quality of information is measured with the help of an Information-Quality framework. This framework contains the four target categories Accessibility, Representational, Intrinsic and Contextual, whereby each category can be described by different dimensions. Using this, the available level and quality of information to an instant in time during the product development process can be determined.

Second, specific requirements on information to perform a functional, design or a process FMEA are defined and evaluated by using the IQ-Framework too. So for every type of FMEA a needed level on quality of information is specified.

Third, the available and needed quality of information to perform a FMEA is compared. Based on that, for each type of FMEA the most appropriate period of time during the product development process can be estimated, whereby a contribution for a robust design of products is made.

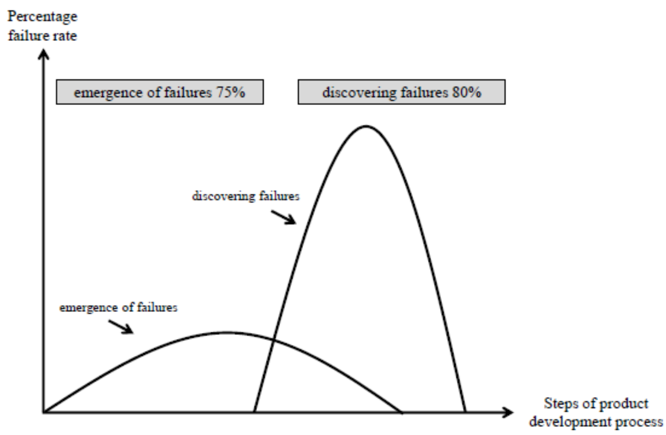
DOI:10.4122/dtu:2095

Reviewed by: *Andreas Dagman*
Søren Nygaard Pedersen

Cited af follows: Würtenberger, J. and Kloberdanz, H., 2014. An approach to identifying the ideal time to perform an FMEA during the product development. In: Howard, T. J. and Eifler, T., ed. 2014. *Proceedings of the International Symposium on Robust Design - ISoRD14*. Copenhagen, Denmark. pp. 79-89.

1. Introduction

Failure Mode and Effects Analysis (FMEA) is a way of detecting and analysing failures that occur during the product development process. Failures and their risks to the customer are identified and valued in order to define mitigation strategies that minimize or prevent failures (Schäppi et. al., 2005). Failures are deviations between the actual status and the desired status of a product property. In practise, there is a gap between the emergence and the discovering of a failure (Figure 1).



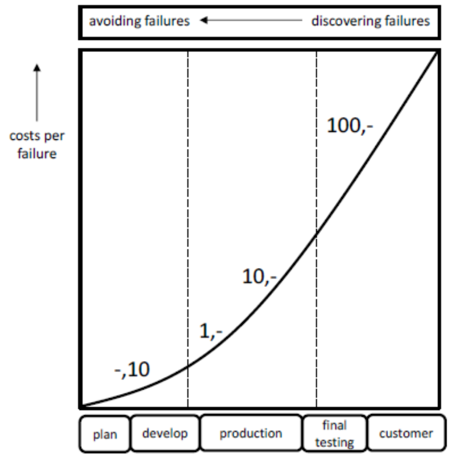


Figure 1. Emerge and discovering of failures [Pfeifer 2001]

Figure 2. Costs per failure [Pfeifer 2001]

The point of detection of a failure is important because the costs of failure grow by an approximate factor of ten as the product development process proceeds (Figure 2). The earlier a failure is identified during the product development process, the lower the resulting costs of rectifying it. Detection should focus on discovering failures rather than avoiding them. Within the quality management framework there is significant economic potential in avoiding failures (Göbbert, 2003).

If the FMEA is used as early as possible, the usable level of information is very low. The level of information grows during the product development process and is understood as all available information, with varying degrees of concretisation, according to a certain instant in time. The growing level of information has an influence on the benefit of the FMEA. If a low level of information is used, the benefit of the results is low too. It is better to perform an FMEA later in the product development process. The literature contains varying recommendations on the best time to perform an FMEA.

The focus of the current research on this approach is on identifying the ideal time to perform an FMEA by analysing the dependencies between the level of information during the product development process, the quality of information and the existing FMEA types.

2. Using the FMEA during the product development process

The FMEA is a systematic methodology to analyze a system in order to identify failure modes and their causes and effects on the rest of the system, such as on the customer. It can be applied at any time during the product development process and contains five working steps. First, with the help of a failure mode analysis, every potential failure of a product that may occur is identified. Effects on the planned usage process for which the investigated product is needed are assigned for each failure. Causes of each failure are identified. Every combination of failure, cause and effect is evaluated with the help of a Risk Priority Number (RPN). The

RPN can be calculated using the probability, severity and detection of a failure. Finally, mitigation strategies are defined in order to avoid or lower severity and detection of a failure (DIN EN 60812 2006).

Depending on the progress of the product development process, different types of FMEA are used. A Functional FMEA identifies functional failures in early design phases in order to identify design weaknesses. With a reduced number of variants during the product development process, a Design FMEA is applied. In this context, structural faults are identified for every product component. (Göbbert/Zürl, 2006). A Process FMEA analyses production and assembly processes of components to detect process-caused faults. Therefore, a comprehensive level of product properties is necessary (Hering/Triemel/ Blank, 2003). The three types of FMEA are interdependent; for example, results of a Functional FMEA are used to perform a Design FMEA. The Process FMEA uses the results of a Design FMEA.

3. Method for identifying an ideal time to perform an FMEA

This paper demonstrates a way to identify an ideal time to perform an FMEA during the product development process, where the conflicting parameters 'costs per failure' and 'level of information' are analysed (Figure 3).

First, it is necessary to systematize the level of information at a certain instant of time. The systematized level of information is evaluated using the Information Quality Framework (IQ Framework). The framework contains dimensions whose trends change during the product development process, rendering the quality of information assignable. Second, requirements for performing a Functional, Design or a Process FMEA are identified. With this help, a comparison between the quality of information at an instant in time and the needed level and quality of information to perform a FMEA is conducted. This makes it possible to allocate the FMEA types to the steps of product development of VDI 2221.A recommendation on which type has to be used according to different points in time is given.

The minimum level of quality of information necessary to perform the chosen FMEA type is also discussed. Trends of the dimensions, such as the costs per failure, are optimized, limiting the possible range of performing the FMEA type. Each of the working steps is described in the following sections.

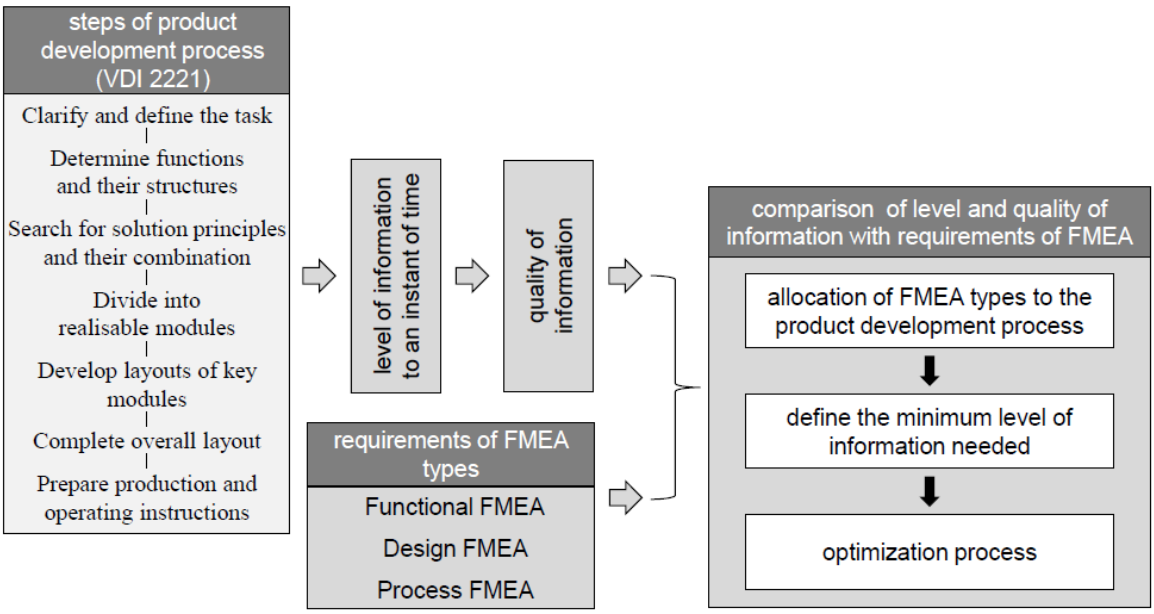


Figure 3. Approach presented in this paper

3.1 Systemizing information levels

Product and process models are used to systemise information levels in the product development process. Product models represent an early stage of the planned product with a certain purpose (Birkhofer/Kloberdanz, 2007); process models describe a time-dependant transformation of an initial state of an operand into a changed final state (Kloberdanz, 2009). This paper describes the adaptation of Heidemann's process model of Heidemann, shifting the focus onto the FMEA (Heidemann, 2001). It gives information about the usage process and the product itself, such as disturbances of product and process. A fundamental aspect of this model is the differentiation between the usage process of the customer and the product produced by the company (Kloberdanz, 2009) so the product itself interacts with the usage process in order to perform it.

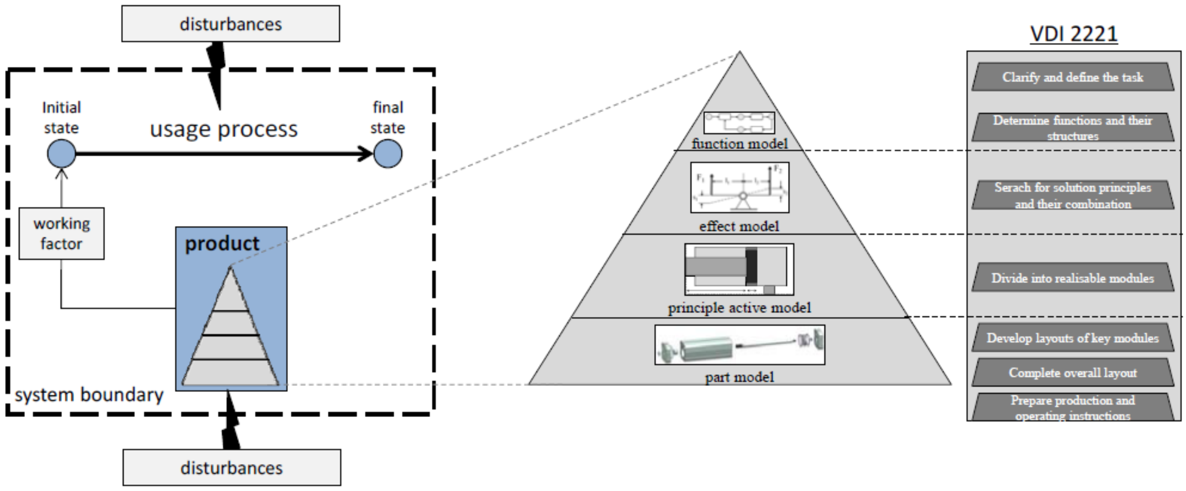


Figure 4. Systemization of level of information [Heidemann 2001], [VDI 2221]

The pyramid of product models is used to illustrate the progress of product development (Sauer, 2006). It consists of four levels: function, effect, active principle and part model. Each model can be allocated to the VDI 2221, which means that the pyramid can be used at any time during the product development process. The function model divides the task into sub-functions in order to describe them objectively. Each sub-function is concretised using physical, chemical or biological effects (Birkhofer/Kloberdanz, 2007). The principle active model combines these effects with material and geometrical parameters, giving a general solution to the task (Birkhofer/Kloberdanz, 2007). All information in the active principle model is specified until the final design of the product is achieved.

With the combined use of the Heidemann process model and the pyramid of product models, all information necessary to perform a FMEA can be systematised to an instant of time (Figure 4).

3.2 Using the IQ Framework to measure the quality of information

After systemizing the level of information, criteria are necessary to measure the quality of information. Mielke et al. developed a hierarchical framework to understand what the quality of information means to the customer (Mielke et al., 2011). This framework contains four categories with 15 dimensions, based on the survey of Wang/Strong (Figure 5). Each category has a specific context.

The category Accessibility analyses how the system deals with information. In this case, it refers to the working steps of the FMEA. The working steps are specified in a norm so their influence on the quality of information does not change during the product development process. This is why the category Accessibility will not be investigated here. The category Representational is also not relevant to this paper as t analyses the way information is presented, which is defined in FMEA worksheets: the effect of this category does not change either.

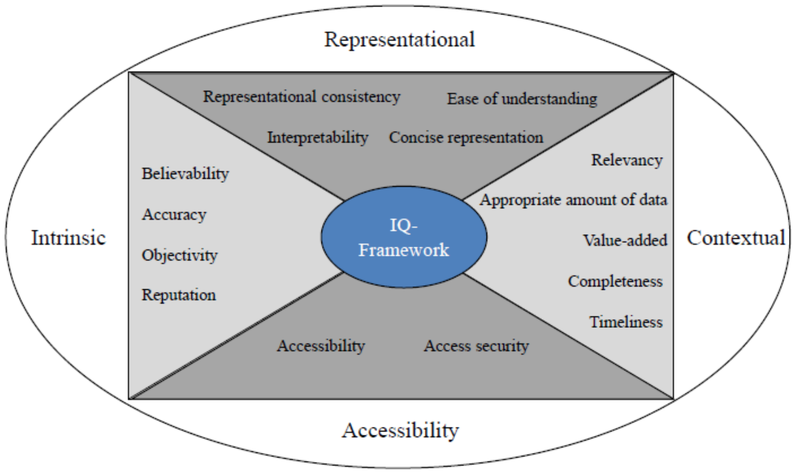


Figure 5. IQ Framework [Mielke et al. 2011]

The categories Intrinsic and Contextual deal with the content and benefit of information, and are the base of this paper. To measure the quality of information, the dimensions have to be applied during the product development process. With the help of the categories Intrinsic and Contextual, the systemized level of information is evaluated and the quality of information at an instant in time can be estimated.

3.3 Analysis of level and quality of information

The changing level and quality of information during the product development process is investigated using Heidemann's process model. The model is applied four times, as described in Figure 5, so that every working step of the VDI 2221 is considered. The quality of information is then evaluated using the dimensions *Objectivity, Accuracy, Completeness* and *Value-added of the IQ Framework* (Figure 6).

The dimension *Objectivity* shows a level of information downward trend with increasing concretisation. This is demonstrated by the decisions that have to be made during the development process. The function model describes partial functions in a solution-neutral manner, where the effect model concretizes them by assigning different effects. For example, it is possible to describe the partial function *transforming an energy* using a hydraulic or mechanical principle so that there are several ways to concretize it. It depends on the developer's view of the problem which effect fits best, which is why the dimension Objectivity shows a downward trend, especially between the second and third working steps of the VDI 2221. The dimension *Accuracy* also declines. With a growing possibility of solutions, the possibility of generating a model grows too, so there is a risk of making mistakes. Because of the dependencies between the product models, there is growing sensitivity along the product development process. The earlier a mistake or an inaccuracy is made, the more serious the consequences. This explains the downwards trend.

The dimension *Completeness* shows a continuously downwards trend because of the growing possibility of generating a model. There is a risk of forgetting an essential effect, which affects the completeness of the following models. The growing complexity increases the risk of missing essential information. Both reasons ensures a downwards trend in the dimension *Completeness*.

VDI 2221	level of information				quality of information			
	product		process	disturbances	Intrinsic		Contextual	
	used model	information			Objectivity	Accuracy	Complete-ness	Value added
clarify and define the task determine functions and their structures	function model	- partial functions - dependencies between partial functions - energies or signals between partial functions - Conduction/ transformation of energies or signals - conduct, convert or link energies or signals within a function	Planned usage process	- function fail - wrong granularity - missing partial function	very high	very high	very high	low
serach for solution principles and their combination	effect model	- physical, biological or chemical effects - parameter of the effects - equations of the effects - dependencies between effects		- missing effects - wrong effects are chosen - conflicting para-meters because of the chosen effects	me-dium	me-dium	high	me-dium
divide into realisable modules	principle active model	- radius of action - geometric of bodies - motions of the bodies - active areas of the bodies - arrangement of the bodies		- wrong dimensioning of the bodies - friction, wear	low	low	me-dium	high
develop layouts of key modules complete overall layout prepare production and operating instructions	part model	- material properties - geometric properties - production methods - tolerances - design principles - assembly instructions		- temperature - corrosion - environmental influences - human influence - unintended effects	very low	very low	low	very high

Figure 6. level of information during the product development process

The dimension *Value-added* grows during the product development process, which is substantiated by the increasing concretion of the models. According to the FMEA, with concrete information a cause of an identified failure and the consequences to the costumer are much easier to identify because of the growing reference to the final product. The known disturbances also increase, which supports the analysis of a failure.

3.3 Requirements of FMEA types

A Functional FMEA is performed as soon as sufficient information is available to construct a functional model, as mentioned in the pyramid of the product models. The following information, as a minimum, is required (NASA, 2014):

- A functional block diagram of the item under development broken down to the subsystem and component level.
- A description of each function depicted in the functional block diagram, including required inputs and outputs for each block.
- The manner in which each of the required outputs can fail.
- The impact or effect of loss of each functional output depicted in the functional block diagram of the instrument.
- The compensating provisions designed into the item to mitigate the effects of a functional output failure.

A Design FMEA is performed when sufficiently detailed design information is available to identify all the constituent pieces and parts of the design item. In addition to the information necessary to perform a Functional FMEA, information about schematics and principles of operation for the design is required (NASA, 2014).
In order to perform a Process FMEA, process inputs, tasks and expected outcomes have to be developed sufficiently. The following information, as a minimum, is required (NASA, 2014):

- A detailed step-by-step procedure and flow chart for the process.
- A description of purpose of each step in the procedure, including required inputs and outputs.
- The manner in which each of the required steps can fail.
- The impact or effect of failure to achieve each output described in the procedure on the item or function being subjected to the process.
- The compensating provisions designed into the process to mitigate the effects of a process step failure.

3.4 Comparison of level and quality of information with requirements of FMEA

With the help of the identified level of information and depending on the progress of product development, the three types of FMEA can be allocated to a stage within the product development process (Figure 7).

A Functional FMEA needs a functional block diagram, including subsystems, such as inputs and outputs that are given by partial functions and their dependencies. The functions have to be described in order to perform a Functional FMEA. This information is also given by the transformation of energies and signals, so the Functional FMEA can be allocated to the first three working steps of VDI 2221.

In order to perform a Design FMEA, information about schematics and principles of operation for the design is required. The listed effects, such as the elements of the principle active model, contain this information so performing a Design FMEA is useful during the working steps three to six.

The overlapping area between Functional and Design FMEA refers to the requirement that the impact or effect of loss of each function has to be known. It is useful to perform a Functional FMEA, by considering the chosen effects, in order to analyse the impact or effect of loss of a function to define mitigation strategies. For example, when a partial function describes an energy transformation, it is good to know how the function is captured in the effect model. If the effect principle of the lever is used, it can be assumed that the customer will not be endangered by fluids. Risk from fluids could have occurred if the partial function is concretized by a hydraulic effect. This is why overlapping performance of the FMEAs is useful here.

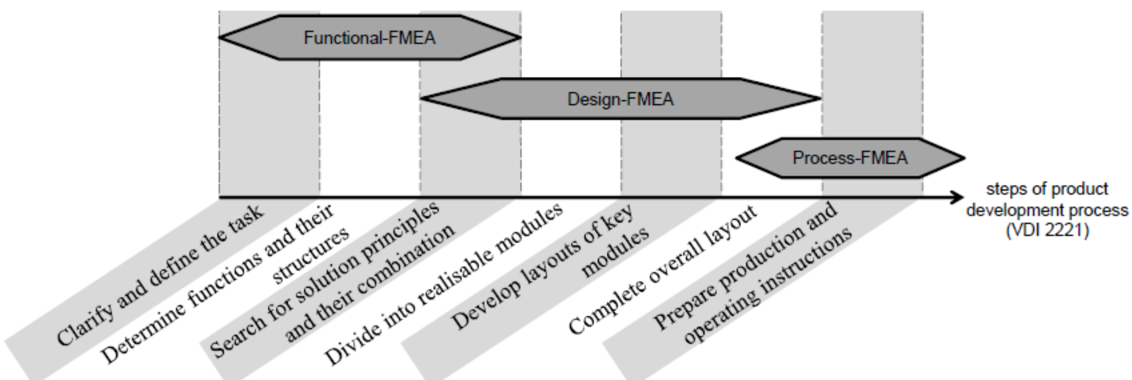


Figure 7. Allocation of the FMEA types to the product development process

In order to perform a Process FMEA, the production process has to be known, so it is useful to perform this type of FMEA at working step seven.

After allocation of the FMEAs to the product development process, a minimum level of quality of information has to be defined (Figure 9). First, the identified trends of the dimensions that represent the quality of information during the steps of product development are put together with the allocated FMEA types.

Compensation provisions have to be defined for each FMEA type. To identify the type, a minimum quality of information is necessary. For example, if a Functional FMEA is performed as early as possible, the Value-added part of the information is very low. Information is Value-added if its use fulfils a monetary objective. According to the FMEA, it is achieved if the information could indicate failures, for example. If it is performed at step one during the product development process, only information about clarifying the task is available. Value-added is very low where an analysis of compensation provisions is not possible, so a minimum Value-added is necessary. For the dimension Objectivity, a contrary argument is conducive. The Objectivity of information declines during the product development process because the modelling of an effect or a principle active model always depends on the point of view of the product developer. This implies that occurring failures cannot be detected, so a minimum level of Objectivity is necessary.

With this help, a minimum level of quality of information can be defined for each considered dimension, which is illustrated by the dashed lines in Figure 9. The possible range needed to perform an FMEA can be identified for each FMEA type, which is demonstrated by the striped area. If the rest of the dimensions are also considered in the optimization process, the possible range for performing a FMEA becomes smaller untl the ideal point in time is realised.
Costs per failure can also be integrated into the optimization process by filling in the cost curve in Figure 8 and minimizing them, as described above.

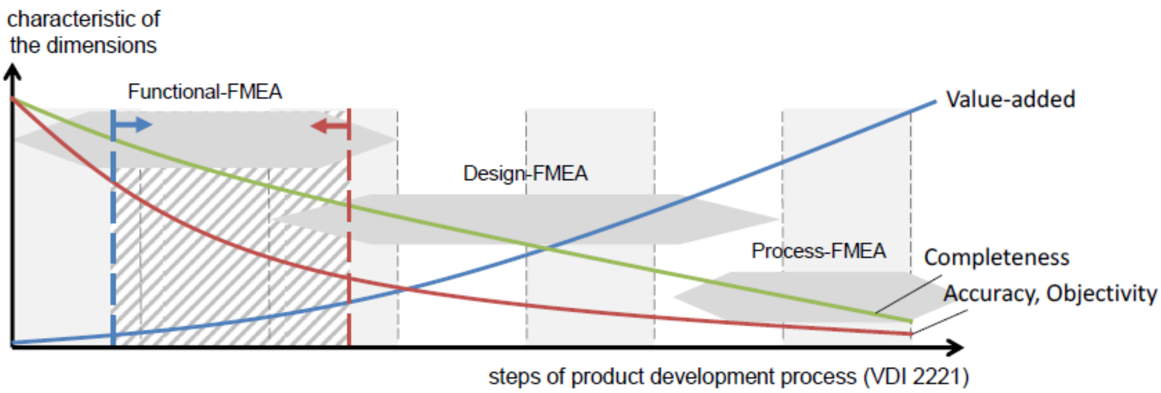


Figure 8.Optimization process to detect an ideal time to perform an FMEA

4. Evaluation of the approach

A pneumatic cylinder is used to evaluate the approach, which has to fulfill the use process lift a load. First, the level of information is illustrated using completed product models (Figure 9). The function model contains four partial functions, where energy is conducted three times and transformed once. The effects *Bernoulli's law, equation of continuity* and *stagnation pressure* realizes the concretization, for example, for the first partial function. In this context, it is possible that the effect stagnation pressure is incorrectly allocated. The allocation of stagnation pressure assumes that the air pressure is injected into partial function one, but it is possible that an allocation to partial function three is preferable. There is ambiguity where the air pressure is injected into the product. Because of the rising possibility of concretizing the partial functions, it could be that the effect *Coulomb friction* is missing. Both show that the dimensions *Objectivity* and *Accuracy* decline.

According to the dimension *Value-Added* the information concretizes the reference to the final product, especially at working step four. The more effects can be allocated to the functions, the better and more complete are the principle active and part models. With the help, the cause or effect on the customer of a failure can be analysed more comprehensively, so the dimension Value-added grows during the process of modelling. As shown in the example, modelling is a process in which information generation is delayed, which is why the dimensions change as well. According to the FMEA procedure, a minimum quality of information is necessary to fulfil the identified recommendations. For example, to perform a Functional FMEA, a minimum level of *Value-added* is necessary. This is accomplished if all partial functions are known, so the minimum level is set at the end of working step two. In the dimension Objectivity, the earlier a Functional FMEA is performed the lower the possibility of allocating incorrect effects.

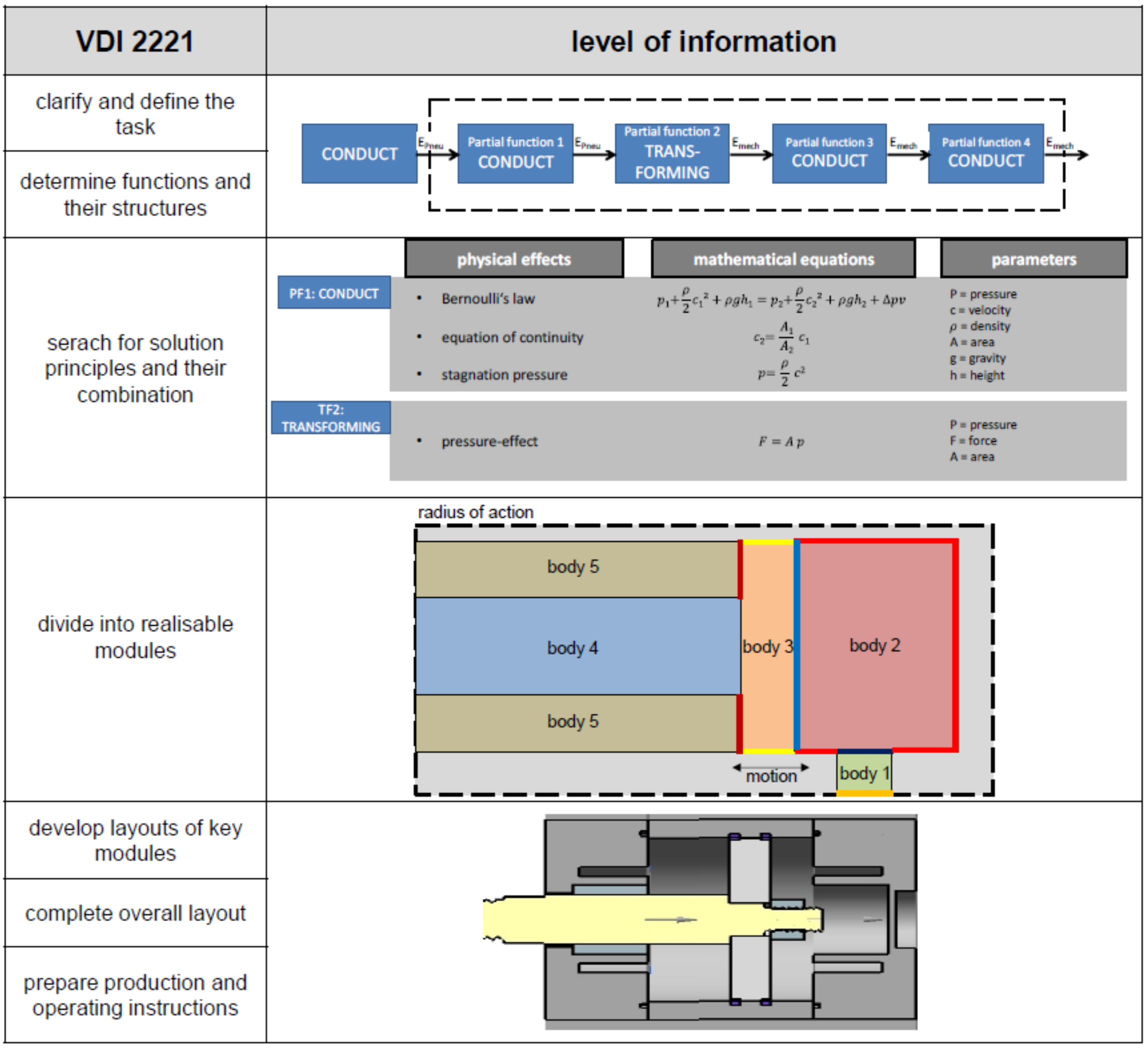


Figure 9. Completed product model of a pneumatic cylinder

5. Results

This paper showed an approach for systemising levels of information, such as the quality of information during the product development process, with the help of Heidemann's process model. Trends of different dimensions were considered. The level and quality of information was compared with the performance requirements of an FMEA. With this, it was possible to allocate the FMEA types to the product development process to determine the minimum quality of information required for each type. By defining the minimum information quality the possible range for each type is limited and can be optimized to an ideal point in time to perform each FMEA type (Figure 8).

6. Conclusions

The results demonstrate dependencies between the level of information, the quality of information using the IQ Framework and the requirements of the FMEA. The dependencies are used to identify trends of the dimensions during the product development process, which are used to optimize the point in time to perform an FMEA.

This is an important contribution to making products more robust because failures are analysed at the right time during the product development process. Designers have to think about the available level and quality of information used to perform an FMEA, so the product itself is analysed before the FMEA starts.

The approach can be used for every type of product where it is possible that the trends of the dimensions do not grow or decline continuously. In this context, more than one ideal point in time for performing an FMEA is possible.

In the future, this approach should be adapted into praxis to evaluate it. The identified trend in information quality during the product development process has to be quantified because the optimization process is based on it. For example, if a scale is defined at the level of information of a dimension the optimization process can be improved.

Acknowledgement

The results of this paper were produced by the Collaborative Research Centre SFB 805 "Control of uncertainty in load-carrying mechanical systems" in the project A1: Development of Models, Methods and Instruments for the Acquisition, Description and Evaluation of Uncertainties. We would like to thank the Deutsche Forschungsgemeinschaft (DFG) for founding and supporting the SFB 805.

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Jan Würtenberger, M.Sc.
Research Associate
Technische Universität Darmstadt, pmd
Magdalenenstr. 4, 64283 Darmstadt, Germany
+496151/16 – 76795
wuertenberger@pmd.tu-darmstadt.de
www.pmd.tu-darmstadt.de