IFMEA – INTEGRATION FAILURE MODE AND EFFECTS ANALYSIS

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ABSTRACT

During the product development process a lot of challenges have to be mastered. Beside ever shorter innovation cycles and time-to-market, products with increasing complexity such as mechatronic products lead to greater development risks. Mechatronic products are characterized by high functional as well as physical (e.g. spatial) integration. This integration of several modules (sub-systems) from different engineering disciplines entails a high risk of product failures. It is therefore crucial to systematically identify these risks already in early design stages. Therefore, it is important to realize that systems (sub-systems, system-elements, modules) are carriers of different physical effects. These effects not only realize the function of the system, but may sometimes have also undesired side effects which may lead to problems for other modules and, hence, have to be considered carefully. In this paper, the IFMEA (Integration Failure Mode and Effects Analysis) method is introduced, which is based on the widespread FMEA (Failure Mode and Effects Analysis) method, but has its focus on identifying problems due to the integration of several modules within mechatronic systems.

Keywords: FMEA, IFMEA, mechatronic systems, integration of subsystems, failure modes, integration problems

1 INTRODUCTION

To assure a successful acceptance in its target market, a product has to fulfill the requirements of the customers as comprehensively as possible. Beside a high cost pressure and short product lifecycles, the challenge lies in developing products with a minimum of failures. Following the ISO 9000 standard [1], a failure corresponds to the non-fulfillment of one or more product requirements, and can have fatal consequences for the product's success. Especially the early product development stages play a key role in this context, because the negative effects and thus also the failure costs (non-conformity costs), i.e. the costs for compensating for the failure, increase disproportionately with the progress of the design activities. This correlation is qualitatively shown in the so called "rule of ten" [2], depicted in Figure 1. Furthermore, the early phases offer a high influence potential on the product at still low accumulated costs ([3], Figure 2).

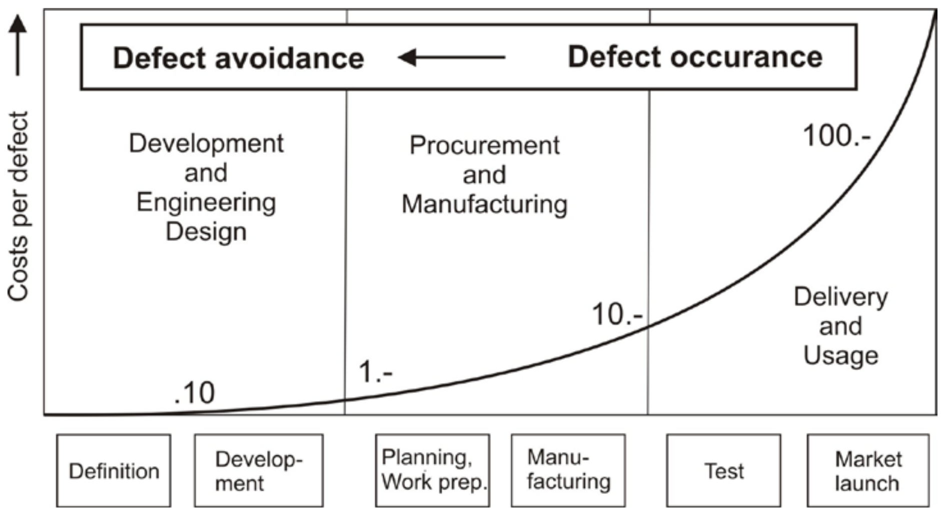


Figure 1. Rule of ten [2]

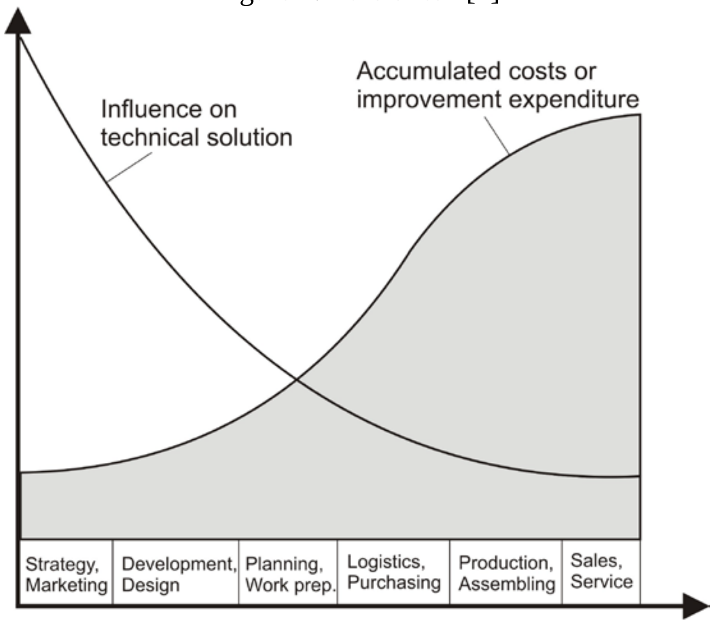


Figure 2. Importance of the conceptual design phase [3]

Failure prevention should generally be given preference over subsequent troubleshooting, because the prevention of failures allows an early improvement of concepts at still relatively small efforts. Appropriate methodological support is offered by the FMEA (Failure Mode and Effects Analysis) method, which supports a systematic examination of potential failure modes, their causes and effects and is summarized in chapter 2.

Nowadays, the complexity of many technical systems increases and the circle of innovation gets shorter and shorter. For example, mechatronic systems are characterized by high functional and physical (e.g. spatial) integration [4], [5]. The integrated modules often originate from different engineering disciplines or represent already mechatronic systems themselves. Their integration can cause problems which in many cases are difficult to identify merely on the level of a single module. This leads to a growing necessity of emphasizing the system level view in product design [6]. Due to the increasing integration of systems expressed by a large number of components which are characterized by extensive interactions and relationships, frequently overlapping many domains, complexity represents a decisive challenge [7] in the development of mechatronic products.

Technical modules (subsystems) are carriers of different physical effects. These effects not only realize functions of the system, i.e. the desired behavior of the system, but may sometimes have also undesired side effects which may lead to problems for other modules in varying extents. One simple example is the breakdown of an electronic circuit because of mechanic vibrations of a different, mechanic module. A systematic consideration of the physical effects - caused by single modules and their interaction - on a specific system level can be helpful to identify and anticipate such failures at an early stage. For this reason, a systematic approach, which supports these investigations, is introduced in this paper.

2 FMEA - FAILURE MODE AND EFFECT ANALYSIS

Failure Mode and Effects Analysis (FMEA) ([8], [2]) is a methodology for identifying possible failures in product design early in the product development process. Thus it becomes possible to identify and overcome problems in early product design stages. FMEA is product- and industry-independent and can be used, for example, in automotive industry, power plant technology, medicine or aerospace applications.

According to [8], the FMEA approach basically comprises the following five steps

1. Structural analysis
   Capture all relevant system elements. Document the system structure.
2. Functional analysis

Assign functions to the system elements. Link the functions and create a function net.

3. Failure analysis
   Assign possible failures to the functions. Link the failures and create a failure net.
4. Risk analysis and consideration of measures
   Estimate and evaluate possible failure modes and consider appropriate measures for their prevention.
5. Optimization
   Ensure the implementation of the prevention measures and examine their results. An unsatisfactory result leads to the consideration of new measures.

Several forms (worksheets) are available to support the execution of these steps. Thus the method helps to detect weak points of the product, at the same time understanding their severity and initiating appropriate measures for their prevention in time. The FMEA methodology offers many advantages in product and process design such as failure prevention in early development stages, capturing expert knowledge, documentation of risks and measures for reducing these risks, saving money due to the reduction of design iterations and improving communication and cooperation between customers, suppliers, development partners, and several departments inside the company.

FMEA methods are successfully used in industry for many years, and several enhanced developments for various applications (e.g. in the fields of Aeronautics and Astronautics [9], or Healthcare [10]) have been published in literature.

3 IFMEA – INTEGRATION FAILURE MODE AND EFFECTS ANALYSIS

3.1 Introduction

The FMEA method offers a well established contribution and a solid basis for the detection of possible failures. Due to the ever higher levels of spatial and functional integration of technical (especially mechatronic) products, the systematic consideration of possible failures caused by the interaction of several subsystems is becoming increasingly important. Unfortunately, the FMEA method supports this aspect only to a certain extent, which leads to a demand on methods explicitly focusing this topic.

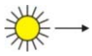
Some of the further developments of the FMEA approach are dealing with the interactions of modules integrated into a system, for example [11]. Following this approach, environmental conditions for components are systematically assessed in a 7-steps-procedure. This allows for identifying risks and considering appropriate protection measures for each module already in very early development stages. However, the examination of the causes of the effects affecting each of the modules is not systematically supported, at least not to the desired extent.

For this reason, the IFMEA approach is introduced in this paper. Similar to the FMEA methodology, the IFMEA approach is a preventive method to identify and prevent potential product failures. Its goal is to examine potentially harmful (physical) effects, which could affect the modules integrated into the system. Each module carries different physical effects with diverse characteristics. Some of these effects are intended, while others are undesired side effects and occur without intension. These side effects don´t contribute to the functions (intended behavior) of the modules or the system. Examples of side effects could be mechanical vibrations, electromagnetic fields or generation of heat. These effects may be spread throughout the system in different ways, e.g., they may be intensified, weakened, accumulated or stored. They can´t be described as harmful or harmless per se, because their negative or even destructive impact always depends on the affected module. If one module generates an effect which is harmful for another module and this effect finds its way from the generating to the affected module, a potential integration problem is encountered. The IFMEA can be considered as an addition to the FMEA method, which helps to identify potential failures caused by the functional and physical integration of different modules in a mechatronic system. Thereby also physical side effects, which don´t support the fulfillment of product functions, are considered. The operating modes of the product, in which the harmful effects occur, are taken into account, too. With the help of forms and an expandable catalog of possible effects in addition to a structured and discipline integrating process model, a good documentation of the considerations can be achieved.

3.2 Processing the IFMEA

The IFMEA approach consists of several steps, which are depicted in Table 1. After defining the system's operating modes, a team of experts systematically examines physical effects caused by the environment, which could affect the system. Therefore a pre-defined and expandable catalog of possible effects can be used. Then, the individual departments which are responsible for specific modules have to examine the effects that could be generated by their own modules. In addition, the harmful effects for each module are considered without paying attention where these effects could arise from. Using this information, potential integration problems can be identified and appropriate measures may be taken.

Table 1. Steps of the IFMEA method

Step	Description of the step	Form existing, symbol	Involved persons	Number of completed forms (at n modules)
1	Clarify target, sequence and the persons responsible for IFMEA. Decompose the system into modules.		All persons responsible for a module + IFMEA team	
2	Determine system operating modes		IFMEA team	1
3	Examine harmful effects of the environment to the system		IFMEA team	1
4	Examine which effects are harmful to single modules of the system		Each person responsible for a module (within the corresponding department)	n
5	Examine which effects are generated by single modules of the system		Each person responsible for a module (within the corresponding department)	n
6	Examine and document potential integration problems		IFMEA team	$n^2 + n$
7	Analyze potential integration problems and check their relevance		IFMEA team	n
8	Find measures to overcome the identified integration problems		All persons involved	

In the following, the single steps are explained in more detail.

Step 1: Determine and communicate the purpose and sequence of the IFMEA. Introduce the IFMEA project leader. Discuss organizational aspects.

Step 2: Determine all possible system operating modes (including manufacturing, assembling, testing, storage, transportation, installation, start-up, operating and loading conditions ...).

Step 3: Examine harmful effects of the environment to the system. What harmful effects generated by the environment can affect the system (including storage, transportation, commissioning, user use and abuse etc.)? In which operating modes can they occur and what is the probability of their occurrence?
Relevant form fields: Effect type, specification of the effect, relevant operating modes, causes of the effect, the probability of occurrence (denoted by the factor A and scaled from 0 to 10 in analogy to FMEA).

Step 4: For each of the modules, examine which effects could be harmful. Which effects are harmful to the module under consideration? Possible sources of these effects are not considered in this step.

Relevant form fields: Effect type, specification of the effect, possible negative consequences to the module, relevant operating modes, probability of negative consequences (factor B, scaled from 0 to 10), severity of the consequences to the module under consideration (factor C, scaled from 0 to 10).

Step 5: Examine which effects are generated by each module of the system. At this point it is irrelevant, whether these effects are harmful to other modules or not.
Relevant form fields: Effect type, causes of the effect, specification of the effect, relevant operating modes, probability of occurrence (factor A, scaled from 0 to 10).

Step 6: Examine and document potential integration problems. Also consider a possible negative impact of the module´s effects on the module itself.
Relevant form fields: Effect type, possible negative consequences to the module, relevant operating modes, probability of occurrence of the effect (factor A, scaled from 0 to 10), probability of negative consequences (factor B, scaled from 0 to 10), severity of the consequences to the module under consideration (factor C, scaled from 0 to 10), can the effect reach the harmed module (factor D, scaled from 0 to 10), integration risk number (IRN=AxBxCxD), causes of the effect, specification of the effect, relevant operating modes.

Step 7: Analyze and discuss potential integration problems to check their relevance. Which integration problems are already irrelevant because of the product concept? (Nevertheless, document and examine them).

Step 8: Find measures that could be taken to overcome the identified integration problems.

In the course of these steps, potential integration problems can be gathered and analyzed. Thereby, also the transmission path is taken into account, which examines if a harmful effect can reach the considered module at all.
A potential problem of integration occurs when

- a harmful effect
- with damaging specification for the affected module
- in the appropriate operating conditions
- with a probability of occurrence A>0,
- a probability of harmful consequences B>0,
- and a severity of the impact C>0
- can find its way from the generating module to the considered module (D>0).

Afterwards, the integration risk number IRN =AxBxCxD is calculated and the potential integration problem is documented. These results can be considered similarly to the results of an FMEA in the further product development.
The method is based on the FMEA in order to offer potential users an easy and fast access. A big advantage of the IFMEA approach is that, due to the systematic use of a predefined effect catalog, each module is considered with respect to different perspectives (electrical, thermal, mechanical...), irrespectively of its intended functions. The combination of this information offers the possibility to recognize potential system-level integration problems, which will be at least incomplete on the level of modules due to the corresponding restricted view. The identified integration risks are often based on legitimate operating conditions of the modules, which means that the harmfulness of one module to another one need not be caused by a malfunction.
As shown in Table 1, at a number of n modules $n^2 + 4 \cdot n + 2$ forms have to be completed in total. The majority of them, namely those from steps 2, 3 and 6, are filled in by the IFMEA team, which consists of the project leader and ideally a team of system engineers. Each individual module leader has to fill in only two forms (one in step 4 and one in step 5). The total number of forms to be processed increases with the number of modules in quadratic order. To keep the effort (respectively

costs) reasonable, the number of considered modules in an IFMEA project should therefore be not too high.

3.3 Possible strategies to overcome integration problems

The execution of an IFMEA points to potential integration problems and their integration risk number (IRN). Similar to the FMEA, this risk priority number ought to be considered as an indication of the importance of the possible failures [8]. In the course of the IFMEA, necessary measures should be considered, which are able to help reducing the importance of possible failures. The integration risk number (IRN) can provide useful recommendations, at which hierarchy level these actions could preferably be performed:

IRN high	Solve the problems on the level of system design. Ensure the avoidance of the problem as early as possible.
IRN medium	Attempt to solve these problems in the conceptual design phase or as soon as possible during domain-specific design.
IRN low	Solve these problems in the course of domain-specific design.

The following measures could be taken to overcome the identified problems:

Option 1	The harmful effect is not produced (factor A) or only in non-harmful specification.
Option 2	The probability of a damaging consequence to the affected module (factor B) is reduced.
Option 3	The severity of the consequences of the harmful effect on the module (factor C) is reduced.
Option 4	The damaging effect occurs only in operating modes, when the module is not vulnerable.
Option 5	Prevent that the harmful effect penetrates the damaged module (factor D).

4 IFMEA – EXAMPLE WASHING MACHINE

The sequence of an IFMEA is demonstrated by means of the mechatronic system "washing machine". First, in step 1, organizational aspects of the IFMEA were clarified, afterwards, the system was decomposed into five modules, see Figure 5. It is important to precisely define the module boundaries.

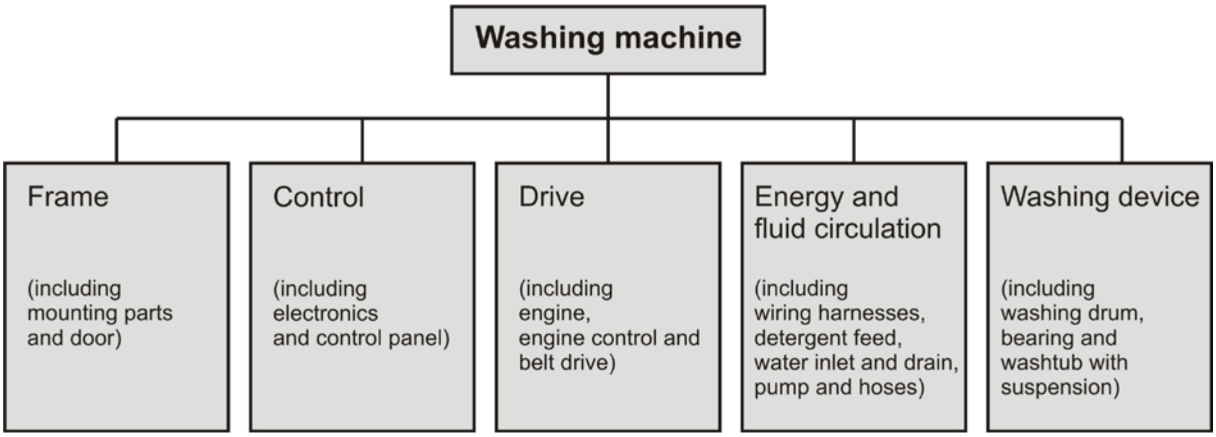


Figure 5. Decomposition of the mechatronic system “washing machine”

In step two, important system operating conditions, for example, transport, installation, washing, spinning and pumping, were examined and documented (Figure 6). After this, damaging effects for the system caused by the environment are considered and documented in the according form. Steps 4 and 5 are then executed by the respective module leaders separately. In step 4, identified damaging effects that can damage the electronics in the “control module”, for example, vibrations or leakages of liquids (water, etc.), are shown in Figure 7. Possible effects, such as vibrations or heat generation, that may be caused by the “washing tub and drum module” (step 5) are depicted in Figure 8.

Definition of operating modes

	Name	Description	Specification
1	Transport, delivery	Transport from the factory to the merchant, and from the merchant to the customer	Loading with forklift; Transport by truck; In any weather (summer,winter, rain...).
2	Installation	Installation process performed by customer or installer.	Possibly Inept handling or inadequate tools
3	Washing	Drum turns slowly; Hot sud in the drum; After washing rinsing with clear water.	Rotation speed XY rpm, Temperature of suds up to 90°C.
4	Spinning	High drum speed; Heating off; Fluid is drained off.	Rotation speed up to 1400rpm
5	Pumping	Drum doesn´t rotate; Fluid is drained off.	Delivery rate of a pump XZ liters per min

Figure 6. IFMEA Form – Definition of operation modes

Damaging effects for the module

Module under consideration: Control module

				Operating modes							
	Name of effect	Specification range of damaging effect	Possible negative consequences for module	all	1	2	3	4	5	Probability of negative conse-quences B [0-10]	Severity of negative conse-quences C [0-10]
1	Vibration, dynamic forces	X Newton, f>5Hz, long period	Module breakdown	X						3-5	10
2	Static forces	Y Newton	Module breakdown				X	X	X	8	6-10
3	Dirt (dust, swarf..)	Small particles	Electric contacts contaminated	X						2	6-10
4	Heat (accumulation..)	T > 90°C	Module breakdown	X						2	10
5	Coldness (icing..)	T < -30°C	Module breakdown	X						2-4	10
6	Fluid (H_2O, oil..)	Small amount	Corrosion	X						2-4	8
7	Air pressure / air flow										
8	Other gases (CO_2..)										
9	Resizing of surrounding area	Small resizes	Circuit board damaged	X						1	10
10	Change of position (inclination..)										
11	Noise										
12	Light (ultraviolet rays..)	Sunlight, long period	Fading	X						2	1
13	Electric current / voltage										
14	Electromagnetic field	Strong field	Module breakdown				X	X	X	1	2
15	Sparking										
16	...										

Figure 7. IFMEA Form – Damaging effects on the module under consideration (control module)

Possibly damaging effects caused by the module

Module under consideration: Washing drum and tub

	Name of effect	Cause of damaging effect	Specification range of damaging effect	Operating modes: module malfunction	all	1	2	3	4	5	Probability of occurence A [0-10]
1	Vibration, dynamic forces	Unbalance+centrifugal force, laundry	XY Newton, up to 1400 rpm					X	X		10
2	Static forces	Weight loaded	XZ Newton		X						10
3	Dirt (dust, swarf..)										
4	Heat (accumulation..)	Bearing friction	Approx. 50°C						X		5
5	Coldness (icing..)										
6	Fluid (H_2O, oil..)	Tub leaking	5 liter of suds, bearing oil	X							2
7	Air pressure / air flow	Spinning	Light air flow						X		10
8	Other gases (CO_2..)										
9	Resizing of surrounding area	Flexible suspension	2 cm in various directions					X	X	X	10
10	Change of position (inclination..)										
11	Noise	Bearing noise, air swirling	Approx. 50 dBA						X		10
12	Light (ultraviolet rays..)										
13	Electric current / voltage										
14	Electromagnetic field										
15	Sparking										
16	…										

Figure 8. IFMEA Form – Possibly damaging effects caused by the module under consideration (washing drum and tub)

After the forms of steps 4 and 5 are filled out for all modules, the IFMEA project team carries out an analysis to identify potential integration problems. Thereby, also potentially harmful effects of each module to itself (for example, heat generated by electronic circuits of the control module could affect its own functionality) are considered. In Figure 9, the form for possible integration problems regarding the "control module" due to effects caused by the "washing tub and drum module" is shown.

Potential integration problems

Causing module: Washing drum and tub
Damaged module: Control module

	Name of effect	Operating modes: module malfunction	all	1	2	3	4	5	Probability of occurence A [0-10]	Probability of negative consequences B [0-10]	Severity of negative consequences C [0-10]	Can the effect reach the module? D [0-10]	Integration risik A x B x C x D
1	Vibration, dynamic forces					X	X		10	3-5	10	10	3000-5000
2	Static forces					X	X	X	10	8	6-10	2	960-1600
3	Heat (accumulation..)						X		5	2	10	4	400
4	Fluid (H2O, oil..)	X							2	2-4	8	2	64-128
5	Resizing of surrounding area					X	X	X	10	1	10	0	0

Figure 9. IFMEA Form – Potential integration problems of the control module due to physical effects of the washing drum and tub module

In step 7, those potential integration problems with an integration risk number greater than zero are depicted in a fishbone diagram (Figure 10). In this representation, further information such as the integration risk number, relevant operating modes or the specification of the damaging effects can be gathered. This allows to clearly display possible failures and their causes with respect to the integration of the modules.

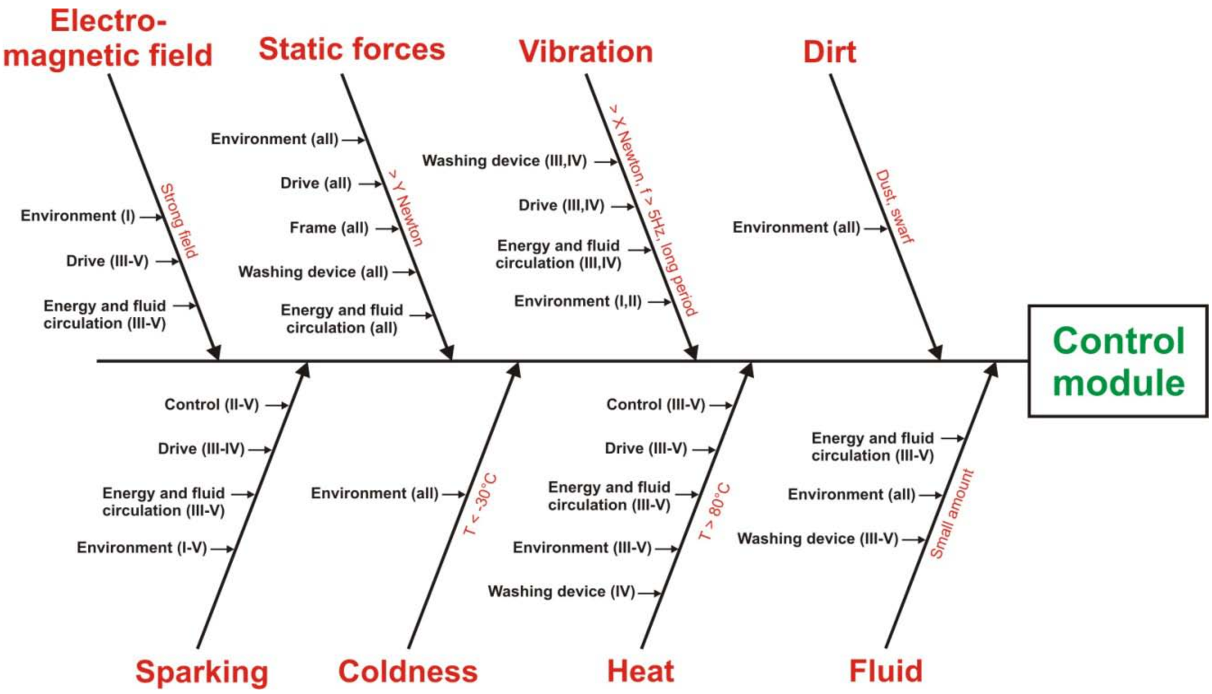


Figure 10. Possible integration problems of the control module due to different physical effects caused by several other modules; relevant operation modes (in brackets) and specification of damaging effects

In the eighth and final step, critical errors can be identified on the basis of the created diagrams and forms, and prevention measures can be developed in team work.

5 CONCLUSION

The prevention of design failures plays an important role in the product development process. For this task, the common FMEA method offers a well established contribution and a solid basis. Due to the ever higher levels of spatial and functional integration of technical products, the systematic consideration of possible failures caused by the interaction of several subsystems is becoming increasingly important. Unfortunately, the FMEA method supports this aspect only to a certain extent, which leads to a demand on methods explicitly focusing this topic.

The method IFMEA (Integration Failure Mode and Effects Analysis), which was introduced in this paper, aims at a systematic identification of possible failure modes, particularly, due to the integration of several modules into a technical system. The procedure of this method consists of several steps, which support the systematic consideration and evaluation of possible integration failures. Therefore a pre-defined and expandable catalog of possible effects can be used. This allows the identification and visualization of possible failures and their causes. Several strategies to overcome integration problems are presented and can serve as a basis for further design activities. The example of a washing machine was used to demonstrate the applicability of this approach.

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