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Failure Classification and Analysis for Technical Products

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Abstract

The paper presents an approach to implement a failure classification and associated analyses for production ramp-up. The structural design of the failure classification is described in terms of a faceted classification by design principles to meet the requirements for the indexing of failure cases and the evaluation of specific failure facets. The structural design of the classification is followed by the design of the content of individual failure facets. The failure facets and their contents are used in the analysis. In this paper, the similarity search and the failure priority analysis are developed as functions, as they are particularly relevant in the ramp-up situation. Conceptual model examinations and case studies are carried out for validation.

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Keywords: continuous improvement, failure management, failure classification

1. Introduction

The presence of the internet of things and services in the factory respectively the digitalization in industry, concerning their products and services is summarized in Germany under the term "Industrie 4.0" [1]. Machines, storage systems and the production facilities will work together in a network as cyber-physical systems (CPS). Real-time systems, the vertical and horizontal integration and the emergence of new business models are some keywords [2].

Important components of this development are sensors as a precondition to realize the promises made under the term "Industrie 4.0". Sensors multiply and simplify the possibilities of data collection. The structure of crosslinked sensors is already part of a new research group. The sensor term is defined widely spread in this context. Sensors include, for example, social media sensors to register the customer comments on defect products. This kind of data collection and the consequent possibilities of data processing help especially in the failure detection and handling. Smartphones, tablets, or other wearables like smartglasses are introduced into the smart factory. As a main application, failure handling is mentioned.

Beside the developments in the industry 4.0 manufacturing companies are in a difficult situation: in the automotive industry and many other industries, technological change leads to a shortening of life cycles and an increasing number of variants through the customization of products. This situation is a major challenge for both ramp-up and failure management. Common strategies try to reduce the complexity. However, the failure modes are highly heterogeneous and the causes are divers. For instance, failures in ramp-up are caused due to issues in engineering, manufacturing and assembly, inadequate maintenance of machines and equipment as well as hardware, software, and operator failures [3].

The following paper provides an approach for the classification and analysis of failures in technical products with a focus on the ramp-up situation. After a detailed problem statement (chapter 2) the literature review is shown and requirements are derived. Methodological aspects are presented afterwards (chapter 4). Chapter 5 introduces the failure classification on which the failure analysis is set up for

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the ramp-up situation. The classification and the analysis are examined in a practical entrepreneurial context which is shown in chapter 7. Finally chapter 8 provides a brief summary and conclusion.

2. Detailed problem statement

The long-term benefit of careful failure and root cause analysis is often not sufficiently recognized due to short-term production targets. An industry study points out that a rigorous analysis of the causes is very rare even in the case of reoccurring failures. The reasons for this can be found in the existing time and cost pressures. High costs for a cause analysis are facing productivity rates or even a production stop. High reject rates are often accepted, although structured failure analysis would prevent future failures and thus could reduce costs [4].

The problem is that manufacturing companies have insufficient structures to realize learning effects from their own failures to improve their processes. This includes in particular the ramp-up process in which the product planning is realized in physical products the first time. In one study, only 22 of 108 companies (20%) are able to reflect their occurring failures correctly. As a result, there is the need for improving the quality of failure detection and classification. After this, improvements can be derived from on a valid failure analysis [5].

Further problems are the failure structure and the failure content description. In many companies, data collection and thus the failure detection is separated into departments (e. g.: in development, in production, in sales departments) or separated due to specific local factors. Moreover, the data structure is heterogeneous and often insufficient for analyzes. The lack of integration of the (partially heterogeneous) data structures in failure management processes is a potential that may arise from the data networking.

This is a contrast to the aforementioned potential of sensors for data collection. The existing data has to be used for the failure description and classification. Failure management can significantly be improved by using this potential. However, it is necessary to collect the right data and to extract the correct data from the plurality of the total data recorded. The typical project approaches like Knowledge Discovery in Databases (KDD) which includes data mining techniques provides solutions. In this approach 75-85% of the total effort are not spend for the analysis, but in steps as the data selection, data preprocessing and data transformation [6,7]. For failure management, which is not in a very crucial task in the company, the use of such project approaches with the necessary human support (expertise) are impractical to answer specific questions in ramp-up.

Fully automated analysis, are established in failure management only sporadically so far. Specific analysis functions, such as supporting the ramp-up process as the critical and most fault-prone phase of production, are not known yet.

3. Literature review and derivation of requirements

A brief literature review in the field of failure management and classification has shown that most of the concepts have not been developed beyond a theoretical prototype and have only found limited or no application in practice [8]. In daily business, the concept often fails due to a not uniform failure recording or description [9]. Regarding this, the precise failure classification is the central element of the overall failure handling process. Due to this lack of clarity, most existing approaches that rely on a uniform classification of failures do not solve the mentioned problems [8].

Concerning this matter, the literature does only enlarge sporadically upon an explicit drafting of failure descriptions. Approaches that, based on a specific example, try to record failures sortable and retrospectively analyzable and try to avoid both, synonyms (comparable situations are described with different terms) and homonyms (different situations are described by the same terminology), are indeed presented, but often do not meet the standard to be transferable to products of other industries.

In preparation of this paper, the authors conducted expert interviews to find requirements in addition to the requirements mentioned in the literature. Those requirements lead to a better understanding what a failure classification and analysis for technical products has to fulfil.

The identified requirements are already presented in further work [8]. In total there are five different categories of requirements: necessity of tasks, responsibilities and competencies (1), possibility for the implementation in existing failure elimination processes (2), easy access for analysis (3), determination of design rules for the classification system (4) and the detailed description for failures, causes and measures of technical products (5).

4. Methodology

Based on the existing scientific approaches (chapter 3) and the expert interviews, the explanatory model shown in Figure 1 is derived. The model presents three core processes, the development, the production and the field support of a manufacturing company. Various failures may occur in all areas. These failures should be handled with a structured failure elimination process [10]. In addition, it is necessary for the company to observe the entire nonconformities. Failures that are caused for example in the development phase become visible in ramp-up the phase or in the field. Therefore there is the need to look at all failures happening across the companies' processes. The observation of the failure events is necessary to detect them and find the right priorities on time and to limit the failures' impact early.

For the elimination of failures as well as for the analysis a system is necessary that fulfills all mentioned requirements and functions. The insights gained must then be transferred to the respective stage of the process, so that actions can be taken there. Within the system, the failures recorded about the failure sensors need to be captured structured. Without a structured recording no meaningful analysis is possible. Failure classification and analysis are sub-elements of the

Quality Backward Chain of Aachen Quality Management Model. Moreover, in the illustrated model the element of adaptation is introduced. The changing range of products and processes requires the adjustment of the classification and analysis system. To this end, the overview of the transformation process in the corporate context is necessary, which can not be ensured at the level of operational modules. Adaptation is necessary for the permanent system usage and therefore centrally anchored in the Quality Backward Chain [11].

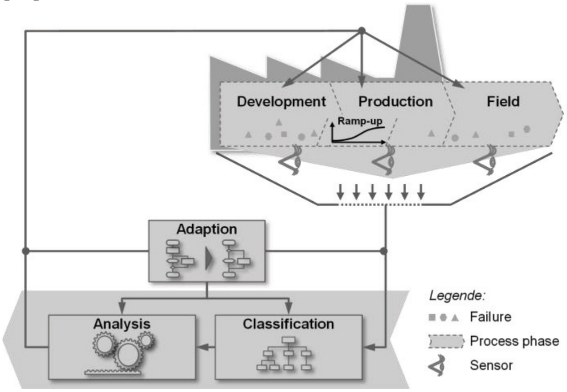

Fig. 1. Epistemological explanation model.

The three elements or areas of activity mentioned are assigned to modules in terms of systems theory in this approach. They are called modules, as they cover each autonomous functional areas within the overall system and have interfaces. They can in principle be replaced by modules with the same function. To convert the elements or fields of activities in the explanatory model in modules of the system, each module has to fulfill the mentioned requirements. This paper focusses on the failure classification and analysis. The adaption will be part of following research work.

5. Failure classification

5.1. Facetted classification

The failure classification scheme is implemented in a facetted classification. A faceted classification uses categories, either general or subject-specific, that are combined to create the full classification entry. Figure 2 summarizes the structure of faceted failure classification clearly. At the top the failure elimination process is structured into three characteristic steps. The first step ends with the failure description in the symptom phase. At this time the failure is not analyzed in a detailed technical way. It is the customers or the sales managers view on the failure. At the end of the failure phase, a technical failure analysis is carried out and a failure description can be made on a technical level. At the end of the action phase, the derived actions are documented with the classification scheme. Each phase ends at a time in the failure elimination process in which the failure has to be classified (symptom, failure, action).

	symptom	failure	action
Product-related failure location	center console	beam	inner beam
Process-related failure location	GWK 6M	inj. molding	maintenance
Product-related failure type	not closing	geometry	
Process-related failure type	-	overfilling	
Failure importance	HF-B	HF-B	P-2
Failure condition	during use	norm	

Fig. 2. Failure classification system.

Failures are classified with facets in each phase of the failure elimination process. As shown in figure 2, some facets are shown. These facets are selected on the basis of specific evaluation by the criteria. The criteria can be separated into cost and quality criteria.

5.2. Construction principles

The facetted classification is built on three main construction principles: hierarchy, citation order and notation.

Each facet is organized hierarchically. This means that the content of a facet (named foci) is selected by going through a hierarchical structure. An example is given in figure 3 which shows the facet "failure location". Failure location means the defective part in a product. Using the structure a bill of material has, the product (SK) is broken down into components (BG) and parts (BT). A main reason for the hierarchical structure is the failure indexing. Indexing means the process of classifying a failure event with the classification scheme. The users' entry has to fulfill quality criteria such as depth of indexing, indexing efficiency and indexing consistency. This criterion does not need to be defined for all facets equally. Indexing depth can vary in the classification less detailed in terms of symptoms than in the technical description of the fault. The quality criteria can be defined differently also depending on the facet.

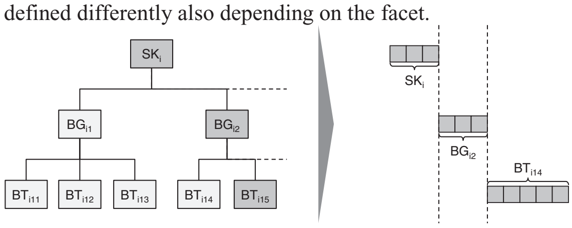

Fig. 3. Hierarchy and notation of the classification system.

The hierarchy can be described by the width and depth. The width is the number of classes within a hierarchy level. The depth describes the number of hierarchical levels.

The principle of citation order means that the contents of the facets are thematically closely linked, standing side by side. "If a user stands right in front a library shelf, he has to find other relevant documents right and left find beside to the direct hit." [12] This principle can be implemented in digital applications as well. For example it is possible to display to the user other relevant content or to use the citation order as a criterion for similarity search respective a similarity ranking. This is different to the approach that is being implemented in typical search engines. In a similarity ranking based on a citation order there are two directions of arranging the results (thematically forward/ up or thematically backwards/ downwards). The content search is not primarily dependent on the similarity of terms, because similar terms do not necessarily have a similar meaning. The similarity of meaning, however, can be mapped on the principle of citation order.

The arrangement of terms should necessarily be carried out in accordance with comprehensible principles. This can, for example, be logical (manager - head of department - group leader – employees), by specialization, by process-orientation (e. g. marketing - development – procurement - production), chronological (failure assessment - failure detection – failure elimination) or partitive (car - drive - motor).

The objective of a notation is the unique identification of failure terms. The notation is the failure key interchangeably and used to uniquely, non-natural language labeling the classification content.

The notation is consequently the leading item of a faceted failure classification. Its design can be very different and is only standardized for special applications (e. g. libraries). In an entrepreneurial context, notation is often called as numbering systems.

Since all facets of the failure classification are structured hierarchical, the notation is performed for each facet alike.

As seen in figure 3, the example of product-related failure location, is designed by the product structure. A distinction is made in product elements, components and parts. For the notation of each component in the hierarchy, a number is assigned. The succession of all numbers forms the notation of the failure location in a hierarchical sequence.

6. Failure analysis in ramp-up

6.1. Definition of potential analysis functions

Analyses in failure management are used for the implementation of failure management functions. Failure management functions are addressing specific business challenges such as predictive analytics, knowledge transfer, or the similarity search in failure classification systems. Depending on the companies needs the necessary functions have to be determined specifically.

An important challenge in producing companies is the management of the ramp-up phase [13]. The ramp-up is characterized by its high dynamic and instability which results mainly from failures and a lack of knowledge. In the ramp-up phase planned processes and products are initially physically created [14]. Failures caused in the planning phases are therefore realized for the first time and have to be eliminated. In this situation a conflict arises between the lack of resources for the management of the ramp-up phase and the objectives of the ramp-up phase (primarily the timely achievement of the ridgeline).

6.2. Setting up the similarity search

In order to resolve this conflict and to create a robust ramp-up, the similarity search is developed as analysis function. The failures during the ramp-up phase usually occur the first time for both the employees of the development project as well as for the production staff. Especially in the automotive industry with development project durations of three to five years, the employees experience is just based on a little number of ramp-up situations. It is very difficult to use personal knowledge and experience systematically in a company. But the use of experiences from previous ramp-ups is very important. The most important precondition for the use of this knowledge is the quick and accurate identification of already processed failures.

The objective of the similarity search is to find failure cases in a case database that are similar or identical to a reference case. The similarity search has two main focuses for its application. On the one hand it serves in the phase of symptom description to identify potential failures based on cases with similar symptoms and thus to define solution managers. Here, similar symptom pictures are sought that have already been processed, so that the associated failure can be selected as a potential failure of the reference case. On the other hand the similarity search can provide solutions. The case based reasoning method is used to realize this function in this research work.

6.3. Example for the similarity search

For the classification shown in figure 2 the following example (see. Table 1) is applied with a selection of five failure cases x_1 to x_5 and the reference case y. The facets in the classification are defined by:

- *Product-related failure location:* beam , stabilization, bracket, cover , arm rest, lock, ventilation duct, faceplate LED, faceplate phone , faceplate USB
- *Product-related failure type:* damage , surface , communication errors, geometry
- *Process-related failure location:* injection molding, painting job, laminating , joining, assembly, packaging
- *Process-related failure type:* overfilling, underfilling, missing paint, inclusion, paint runs, sieve failure, film thickness, assembly sequence wrong, not mountable, handling, packaging
- *Failure importance:* KF, HF-A, HF-B, NF-A, NF-B (KF: critical failure, HF: main failure, NF: minor failure)
- *Failure condition:* environment , stress, time interval, operation, norm, training , test series

Table 1. Similarity including and excluding citation order.

	failure facets						similarity	
case	product-related failure location	product-related failure type	process-related failure location	process-related failure type	failure importance	failure condition	excluding citation order	including citation order
ω	0,2	0,2	0,1	0,1	0,20	0,20		
x_1	beam	geometry	inj. molding	underfilling	HF-B	norm	0,70	0,94
x_2	stabilization	damage	assembly	handling	HF-A	test series	0,20	0,28
x_3	beam	damage	assembly	handling	HF-A	norm	0,60	0,68
x_4	bracket	surface	inj. molding	overfilling	NF-A	training	0,20	0,30
x_5	stabilization	surface	paint job	sieve failure	NF-B	norm	0,20	0,42
y	beam	geometry	inj. molding	overfilling	HF-A	norm		

To focus on one or more facets during the search of similar cases, a weighting is useful. This is particularly useful for the product- and process-related types of failures and failure locations because of their possible dependence among themselves. In practical use, this applies to the process-related failures substantially. The weight is called ω in table 1.

The weighted similarity can be calculated as [15]:

$$sum(x,y) = \frac{\sum_{i=1}^{n} \omega_i sim_i(x_i, y_i)}{\sum_{i=1}^{n} \omega_i} \quad (1)$$

$$with: sim(x,y) = 1 - \frac{dm(x,y)}{n} \quad (2)$$

$$and: dm(x_i, y_i) = \begin{cases} 0 \ if \ x_i = y_i \\ 1 \ if \ x_i \neq y_i \end{cases}. \quad (3)$$

This calculation is weighting the individual facets with the weight ω. Assuming, in the example in Table 1, the process-related failure modes (location and type) are in dependence among themselves; their weight is less than the other. The similarity value for the case x_1 is 0.7. The weights can be specifically selected according to analysis objectives.

In a next step the construction principle of citation order is implemented in the classification. Here thematically related foci are placed side by side or arranged in sequence (see chapter 5.2). This can be demonstrated with reference to the failure importance. The foci of the failure importance are descending according to the importance of the failure: KF > HF-A > HF-B > NF-A > NF-B. If the foci are linearly arranged their values are 4 for KF and 0 for NF-B. The similarity of the facet error score (FB) is calculated as:

$$sim_{FB}(FB_1, FB_2) = 1 - \frac{|FB_1 - FB_2|}{4} \quad (4)$$

In this example, the implementation of the citation order for failure importance, the process-related failure location and the process-related failure type leads to the results shown in Table 1 in the last column.

The result of the similarity between the reference case y to case x_1 improved through the implementation of the principle of citation order to 0.94. This is due to the fact that for example in the facet of failure importance in the case x_1 the deviation without citation order is evaluated with 0. Including citation order, the value is calculated with:

$$sum_{FB}(FB_{x_1}, FB_y) = 1 - \frac{|2-3|}{4} = 0,75 \quad (5)$$

This improves the total similarity search.

7. Validation

For the validation of the research two methods were carried out according to Arbnor & Bjerke [16]. During the research process a conceptual validity check was conducted. For the final results, case studies were carried out.

For the conceptual validity check, structured expert feedback from business practice was taken into account. This feedback is used for the iterative testing of the developed model and its individual components. The validity and applicability of the model and the model's elements was tested by the experts on a conceptual level.

The procedure is used for quality assurance of the research already within the research process. A total of 29 individual tests were carried out with experts from 11 companies. The names of the experts and the companies are not given for reasons of privacy.

All tests were performed bilaterally between the experts and the researchers, usually on site at the company. The modules or activities were presented by the researchers and were evaluated qualitatively by the experts. The experts were able to contribute their personal experiences regarding the applicability of the model. The applicability was discussed by criteria such as the relevance, functionality, efficiency or practicality

The case studies were carried out for both, the classification and the analysis. The applicability of the model in the company is the underlying hypothesis that is verified by the case studies in individual cases. This hypothesis can be assumed to be valid until it is contradicted by other applications.

The first case study describes the implementation of the classification module in a steel manufacturer. The aim of the project was the full implementation of the failure classification at one plant in Germany. As a result of the implementation of the failure classification, the quality of the failure reports, the failure description and the quality of the analyzes could be improved significantly. 10 % of the usual business failures which are classified as "other failures" were clearly assigned. In addition, linguistic deficiencies could be corrected and clearly transposed by the construction principle of the notation.

The second case study describes the implementation of the analysis module for a manufacturer of high-precision plastic components. The aim of the project was to identify measures to reduce the costs of the destruction of defective products.

For the most important failures in the injection molding and printing processes a similarity search was conducted. For this purpose, various failure facets were sorted by the principle of citation order. In addition to the failure facets, specific failure information of the production orders were used (e. g. job numbers, failure cost per case etc.). This information was divided into classes using statistical methods. These classes were arranged by the principle of citation order.

By conducting the similarity search, similar failure cases could be identified (particularly those with high failure costs). This improved the data basis for the derivation of specific actions in the company.

8. Conclusion

Within this paper, research results of an ongoing research project have been presented. Based on a detailed problem statement, a literature review and derivation of requirements were described that are built up from further work.

Based on these requirements, a framework has been developed using the structure of the failure elimination process. Each process phase of the failure elimination process (symptom description, failure description and action description) can be described via different failure facets. In addition the construction rules and criteria for the classification have been presented.

The failure facets and associated foci are used for the analysis to realize specific failure management functions. For this work, the similarity was presented using case based reasoning techniques. The whole process of the classification and analysis development was accompanied by the examination of the results by experts as part of the conceptual validity check. Moreover, the results have been implemented and evaluated using case studies. These activities are the necessary conditions for the validation of the model.

The presented method is new in the field of failure management. Using this method, failures can be described continuously during the failure elimination process. All failure information can be used cross-departmental. Facets and foci are independent from each other and can be adopted or changed due to external influences or new requirements. Using this approach the failure data will be homogenous. This failure data can be provided for an analysis to detect crucial fields for continuous improvement.

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