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A METHODOLOGY TO EVALUATE THE STRUCTURAL ROBUSTNESS OF PRODUCT CONCEPTS

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ABSTRACT

The success of a company is sustainably dependent on the robustness of their products. Product concept should be designed adaptable for initiated changes but resistant against unforeseen changes. But how can product structures be evaluated whether they are robust? In this study, we present a methodology to evaluate the structural robustness by modeling and analyzing dependencies of product concepts in Multi-Domain-Matrices. We conducted four empirical case studies in industry to test and refine the methodology. The proposed methodology enables engineers to (1) to evaluate the structural robustness of product concepts in early phases, (2) to compare different product concepts in term of their structural robustness, or (3) to deduce improvements towards enhanced structural robustness systematically. The methodology can be applied in all phases of product development process. It supports sustainably the improvement of the product architecture, reduction of change costs, decision making in development processes, and systematic deduction of design guidance.

Keywords: Structural Robustness, Complexity Management, Product Architecture, Case Study

1 INTRODUCTION

A robust product concept conduces sustainably to the success of a company. With prudently designed products in the portfolio, both extensive efforts for changes can be mitigated and the flexibility towards changing market needs can be improved. Particularly in times of mass customization [19] and volatile, globalized markets, the efficient management of product changes is a competitive advantage. As early as in the concept phase of product development, engineers can set the course for an adaptive and robust product structure. Therefore, the architectural options have to be made transparent, how they can contribute to more flexibility and structural robustness.

But how does the designer know if a concept is “well” or “badly” adaptable to changes? Lindemann and Reichwald [12] depicted that changes can arise from mistakes and from innovation. Eckert et al. [5] speaks of *initiated change*, which arises from new customer requirements and needs, and *emergent change*, which responds to weaknesses in the product. How can the robustness of a product be evaluated whether the concept is robust against unforeseen changes but flexible enough to allow planned adaptions during the product lifecycle?

All elements in a product concept – ranging from requirements over the functions and components to the production concept to generate them - and the dependencies between them condense in a complex structure. The complexity emerges inter alia from multiple, non-trivial dependencies between the elements, cycles in cause-and-effect chains, counter-intuitive, dynamic behavior and in-transparency of the system [11]. The complexity of systems makes it difficult to estimate the behavior of a product structure whether a change causes long-distance effects in the structure and requires - at worst - a complete redevelopment or whether a change can be implemented cost- and time-efficient with just minor changes to the overall structure. In this study, we define a product concept as structural robust when it can resist the impact of a change – planned or unforeseen – by affecting a minimum number of adjacent nodes of the concerned elements.

In the field of product design, methodologies to evaluate the structural robustness of product concepts are rare, although, we found literature which deals with related problems and inspired us to adapt ideas to our approach.

Robustness is a phenomenon which is exhaustively researched in the past. Otto and Wood [16, p.980] define the task of robust design as the selection of “*a best set of nominal configuration parameters that satisfies the performance specifications with minimum deviation due to manufacture, material or* *use variation*". In quality management, products, processes or systems are considered to be robust, when they are tolerant against noise [14, 15, 21]. Three types of noise can be expected in product development [16]: Manufacturing noise (e.g. process variations), internal noise (e.g. wear), and external noise (e.g. user interaction) cause deviations from desired values. The less such a noise factor can cause a deviation, the more robust a product, system, or process is. This statistical approach obtained broad acceptance in industry and flow into management approaches - besides others - like Six Sigma which was developed 1986 by Bill Smith at Motorola Company.

Nevertheless, quality management methods do not provide guidance how to set up robust product structures. From a different perspective, the robustness of structures was addressed by Agarwar et al. [1] who investigated the vulnerability of structural systems like mechanical frameworks and the impact of relatively "*small damages (that) cause major structural consequences*". They provide a theory of structural vulnerability and developed process model for the search of total failure scenarios. Baker et al. [2] proposed a framework to assess robustness on the basis of decision analysis theory. Basis for a formulation of a new metric for robustness was a probabilistic risk assessment concept. They define an index of robustness as the "*fraction of total system risk (of failure) resulting from direct consequences*".

At the Engineering Design Center of the University of Cambridge, a researcher group [4, 5, 24] examines change propagation in complex structures. Clarkson et al. [4] propose a methodology to cope with changes by capturing likelihood and impact relationships between components and deducing a predicted risk of change or the probabilistic cost of change. They showed methods to derive and analyze propagation trees, developed a software tool (Cambridge Advanced Modeler), and give further implications for re-design and project management [24]. Although, changes may occur in additional domains of a product concept other than components (e.g. requirements, functions, manufacturing steps), we build up on several ideas of their research and adapt some basic concepts.

There is a wealth of literature which provides guidelines, how to design technical products starting from the early phase (e.g., [3, 10, 16, 17, 20, 23]). However, few methodologies can be found (1) to evaluate the structural robustness of product concepts in early phases, (2) to compare different product concepts in term of their resilience to unforeseen changes and their adaptability to earmarked changes, or (3) to deduce implications for product improvements toward better structural robustness systematically.

By applying methods of structural complexity management, we make dependencies in a product concept transparent and facilitate the systematic evaluation of different configuration options of product concepts. Therefore, we propose the central question to be researched in this paper:

> *How can product structures be evaluated whether they are designed robust in order to resist emergent changes and to enable initiated changes efficiently?*

In chapter 2, we present a procedure how to specify the product structure and propose an algorithm to define an index for structural robustness. After selected interpretations and visualizations are shown, we test our evaluation methodology in four different case studies in industry that we conducted within a research project. The following chapter discusses the strength and weaknesses of the approach. In the conclusions, we give prospects for further research.

2 ASSESSMENT OF STRUCTURAL ROBUSTNESS

The overall objective of this study is to develop a methodology to assess product structures in terms of their robustness against changes in the product life cycle. Changes – both earmarked and unforeseen – may cost effort, are time-critical and can have unexpected impact on the product performance. Therefore, five principal strategies can be deployed to cope with changes [8]: prevent changes, front-load changes, assess the necessity and benefits, implement changes efficiently and learn from previous changes to improve the efficiency and effectiveness of future changes. The avoidance of changes of a product during its life cycle is not imperatively worthwhile. Excluding classical unforeseen failures and unless products can be kept simple to fulfill customers' demand over its whole life-span, that no planned change is necessary, changes keep a product adaptable, flexible, and competitive. More important are the efficient control of changes and the ongoing improvement of change management by learning from preceded change projects, which may lead to a competitive advantage for a company. If product modifications occur, the propagation of changes should be transparent, manageable and the implementation should be executed in a cost-efficient way. Unforeseen changes like failures of a component should end in a controllable state of the product. The methodology for Assessment of Structural Robustness (*AStRo*) is presented in this paper. *AStRo* supports the designer (1) to create robust structures for new product development, (2) to evaluate existing products from a structural perspective or compare different product concepts in terms of their structural robustness, and (3) to apply systematically improvements to the product structure.

To analyze the robustness of product structures against changes, we chose a matrix-based approach which facilitates a domain overarching analysis of relations in complex products. A domain "*represents the primary classification of elements*" [11, p.77] –in other words - a set of elements of a certain aspect of a system (which could be, e.g., processes, components, people, documents etc.). Eichinger et al. [6] and Lindemann et al. [11] introduced the Multi-Domain-Matrix (MDM), which combines Design Structure Matrices (DSMs) and Domain Mapping Matrices (DMMs). Matrix-based approaches are applied in related issues like product modularization [7], technical interactions in products [18] or change propagation in technical products [4].

Changes can evolve in different domains of a product concept. Zakarian et al. [26] developed a system robustness matrix which focused on the components domain of a product structure. In our study, we define the domains *requirements, functions, components, manufacturing steps,* and *production resources* as the relevant (compare, e.g. Axiomatic Design, [20]) while an addition or elimination of domains can make sense for specific issues. The set of domains can also be extended by additional domains. In our case studies, where we applied and tested the methodology, we worked with the same domains as defined above, because the robustness of the whole product-production-concept was in scope. Malmqvist [13] gives an overview of matrix-based modeling methods and how various scholastics used different sub-matrices.

In order to assess the structure of a product concept the designer should go through the following steps:

- **System Modeling**: Define elements in each domain (requirements, functions, components, manufacturing steps and production resources) and qualify/quantify the dependencies between the elements
- **Calculation of Structural Robustness**: Compute the impact and the probability of each element and condense the value for the structural robustness index
- **Visualization**: Plot the robustness profile of the product concept and the robustness graph
- **Analysis and Definition of Measurements**: Adjust depth of analysis to the current information need, categorize the elements and determine improvement strategies accordingly

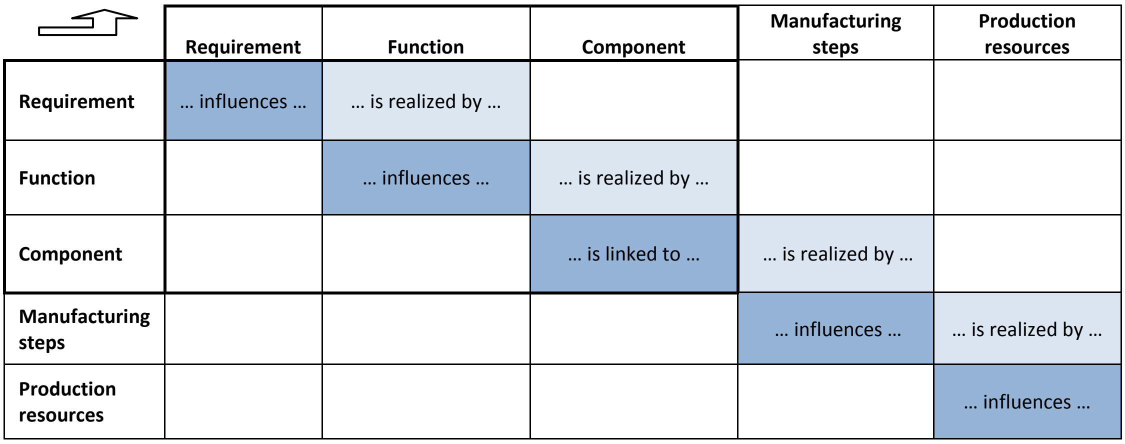
Each step will be explained in detail in the following paragraphs.

2.1 System Modeling

Basis for the analysis is the generation of the product structure itself. To translate the product structure into matrix-form, available data and information have to be collected: All requirements (of a comparable degree of abstraction), functions of the product and the components (or submodules) fill the first three domains of the MDM. To include production aspects in the product concept, the manufacturing steps and associated production resources are depicted in the MDM accordingly. All these elements represent the nodes of the corresponding graph [11]; the relationships between the elements are represented by edges which connect the nodes. Those edges can be undirected or directed, while the later describes the coherences usually more realistic. Optionally, the dependencies between the elements can contain weighting factors to quantify further aspects like severity of change or cost of change. Child-parent-relationships should be avoided to keep the model calculable and consistent (compare [10] and [17]). The meta-model (Figure 1) displays the interpretation of the relationship between the elements.

To evaluate the structural robustness of product concepts, the DSMs on the diagonal and the adjacent DMMs have to be filled with data. The Design Structure Matrices which map the internal dependencies of each domain are described individually in literature (compare [13]). To fill the sub-matrices of the MDM, one can make recourse to already existing documents like, e.g., a Quality Functions Deployment (QFD), a functional relationship model, or a component-function mapping (compare [13]). For example, the DMM which maps requirements and functions is part of the House of Quality. The dependencies between functions and components are described by Ulrich et al. [22] and serve for modularization purposes. Which component is realized by which manufacturing step is

defined in manufacturing planning sheets. Last but not least, the production resources needed to execute the manufacturing steps are described in a production resource planning matrix.
If the dependencies in certain sub-matrices are unknown, workshops with experts could deliver corresponding information. The effort to collect data should correspondent to the information need of the current development phase.



	Requirement	Function	Component	Manufacturing steps	Production resources
Requirement	… influences …	… is realized by …			
Function		… influences …	… is realized by …		
Component			… is linked to …	… is realized by …	
Manufacturing steps				… influences …	… is realized by …
Production resources					… influences …

Figure 1: Meta model of the product structure

2.2 Calculation of Structural Robustness

In order to calculate the structural robustness of a product concept against changes two essential aspects have to be taken into account: keeping the idea of a Failure Mode and Effect Analysis (FMEA, e.g. [9]) in mind, the crucial factors are the *probability* that a change occurs at a certain element and the *impact* of that element on the structure. Also the approach of Clarkson et al. [4] seize on these factors to compute the change propagation and the related change trees.
All dependencies of an element in the row of the MDM can be interpreted as its *exits A* where the element has an effect on; the values in the column of the MDM – analogue – as its *inputs E* of elements that have an effect on the element. The inputs and exits of an element x can be visualized in a sorted graph representation of the MDM (Figure 2). On the left side, those elements are listed which have an influence on element x when they are changed. On the right side, all elements are shown which are influenced when element x is changed.

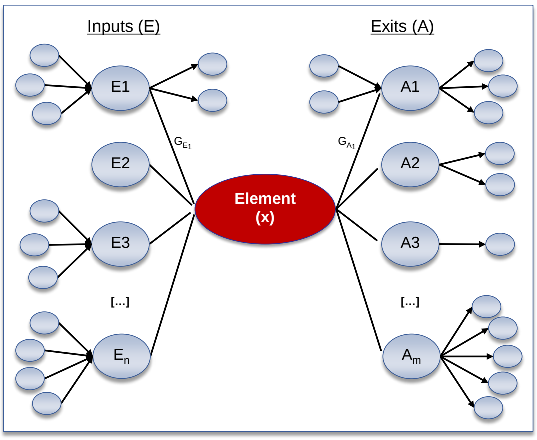


Figure 2: Impact of an element of a product concept

Therefore, we define the impact of an element X as the sum of the (weighted) impact factor of its *n* inputs E and the sum of its (weighted) impact factors of its *m* exits A.

$$I\,(X) = \sum_{i=1}^{n} G_{E_i} * I(E_i) + \sum_{i=1}^{m} G_{A_i} * I(A_i) \qquad (1)$$

Whereas *G* can be a freely selectable weighting factor.

In order to compare the role of each element in the network, the impact of an element is normalized to the aggregated impact of all *n* elements.

$$I'_X = \frac{I(X)}{\sum_{i=1}^{n} I(X_i)} \qquad (2)$$

The second factor is the probability of change. For change propagation, Clarkson et al. [4] suggests to define the likelihood as "*the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface*". The values for likelihood are "*derived from a history of previous design changes and from the views of experienced product designers*" [4]. Although this approach seems to be feasible and could be included in deeper analysis of structural robustness, the effort for defining the values for the likelihood of propagation at each interface is comparatively high in early phases. The calculation of the structural robustness index should be automatable to be a first indicator within easy reach.

Further, we define the probability of an element to be affected by a change as

$$P_x = \frac{\text{number of inputs of element } X}{\text{number of possible inputs of element } X - 1} \qquad (3)$$

This assumption is made to keep the calculation of a robustness index simple in early phases. The concept of the probability can be further refined. Clarkson et al. [4] proposed a feasible option by reflecting lessons learned and opinions of expertise. Our further research is focused on the definition of presumable change scenarios - also based on expertise – and the further refinement of the quality of change (compare chapter 4).

In conclusion, for an *index of structural robustness* (R_{str}), we propose to sum the products of normalized impact and related probability of each of the *n* elements and subtract the result from the unit square.

$$R_{str} = 1 - \sum_{i=1}^{n} I'_{X_i} * P_{X_i} \qquad (4)$$

The product of normalized impact and probability is called *Impact Expectancy Value* (IEV).

R_{str} can range between the two idealized values "0" - non-robust, all changes affect the whole structure – to "1" – changes do not have any impact on the structure at all. For example, if a production resource of a complete robust product concept is changed, no other element has to be changed; whereas a non-robust product concept would have to be completely redesigned.

If the information need requires further details, the following steps can be performed.

2.3 Visualization

Equation (4) above can be interpreted graphically. Each product of normalized impact and probability represents an area, which fills the unit square. The higher the impact of an element is, the lager the width; and the higher the probability of change of an element, the taller the height of the area. For an interpretation in terms of structural robustness a higher coverage of individual areas of elements means less robustness against changes of the structure (compare Figure 3).

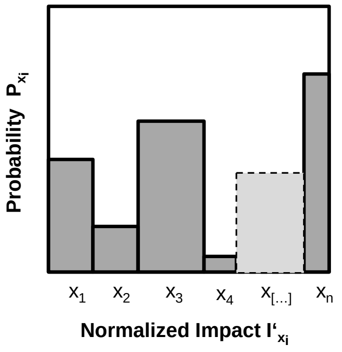


Figure 3: Graphic interpretation of the structural robustness of a product

Another way to visualize the robustness of a product concept is to plot the corresponding graph with colored nodes in accordance to the related IEVs of the elements. This graph is called the robustness graph. The depiction of the IEVs in a graph supports the development team in discussions about critical elements or net configurations and enables a deeper analysis of the product concept.

2.4 Analysis and Definition of Measurements

The step of analysis and measurements definition can be separated in two major aspects: The analysis of each element and the evaluation of the structure in toto. Leading issues in this step are which elements are critical and how should we deal with them in order to improve structural robustness? And how can the structure of dependencies contribute to an enhanced structure of the product concept?

2.4.1Analysis of critical elements

Initially, we make a categorization of elements and plot all elements of a structure in a portfolio spanned by the normalized impact and the related probability of a change of element x (Figure 4). The average probability and the average normalized Impact divide the portfolio in four different areas.

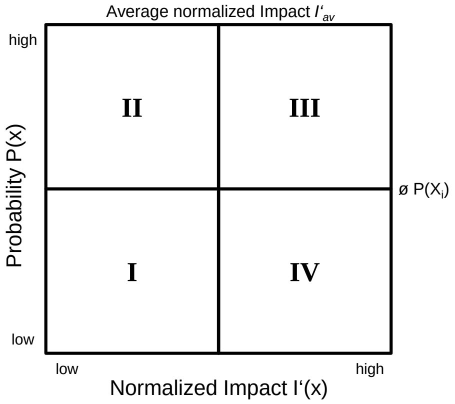


Figure 4: Critical Elements Portfolio

For the four different areas, generic strategies how to perform with elements of the particular area can be formulated:

- **Area I** (Low impact – low probability):
    - Design elements as buffer against failures
    - Exploit as options for customization
- **Area II** (Low impact – High probability):
    - May use as predetermined breaking point
    - Design accessible for redesign
- **Area III** (High impact – High probability):
    - Protected from emergent change
    - Reduce dependencies to adjacent elements
    - Antedate initiated changes in early phases to keep change project cost-efficient
    - Avoid life-cycle changes
- **Area IV** (High impact – low probability):
    - Define as part of the product platform
    - Protect from initiated and emergent changes

These strategies should provide preliminary guidance and have to be further refined in terms of the company-specific problems to be solved.

2.4.2Evaluation of the structure

The structure of a product concept may feature a variety of structural significances. Element clusters, cliques, hierarchies, leave nodes, isolated elements and others can occur overlapping in one structure. To better understand the individual influence of different structural significances on the structural robustness, multiple linear regression analysis has to be performed which is subject of ongoing research.

Moreover, by applying *AStRo* to the design of product architecture, engineers can align the change strategy of a product with suitable selection of concerned sub-modules. Ulrich [22] defined four basic types of product architectures: integral, slot, bus, and sectional. Pahl et al. [17] classify modules in term of their functions, i.e. basic, auxiliary, special, adaptive and customer-specific. Starting from sketch, product developers can optimize the embedding of these modules in an overall structure by calculating and comparing the structural robustness index of each possible configuration.

Through the transparency achieved in the preceding steps, the use of the methodology can support decision making sustainably and substantially. Dependent on the underlying problem to be solved, engineers can work on the configuration of the structure and can calculate modification of the structural robustness index with little effort. They can classify elements in the structure and derive guidelines systematically how to proceed with critical or uncritical elements.

Due to high complexity of modern products, the high number of possible elements, and considerable calculation effort the *AStRo* methodology was implemented with an IT tool prototypically. The dependencies of the elements of different domains can be imported and analyzed automatically. We developed an add-on for *Loomeo* which was implemented in Java. Therefore, given the software tool the effort to calculate the structural robustness index is comparably small.

3 EMPIRICAL CASE STUDIES

We applied our methodology to different cases in industries. In order to test the plausibility of the structural robustness index empirically, we conducted four case studies. The aim of this multiple case study was to find out, if the structural robustness index reflects comprehensibly the following hypotheses which are based on Modularization Theory and Axiomatic Design Theory [10, 18, 20, 22, 23]:

(H1) The more decoupled – which means fewer dependencies among the elements – a product concept is the more structural robust is the concept against changes.

(H2) A highly integrated product concept is more vulnerable towards changes – and therefore, less structural robust - than a modular one.

Unit of analysis were comparatively complex products, where the structural concepts ranged from highly integrated to highly modular products. The companies who participated in the research project are operating in Germany in different branches (i.e. automotive, printing technologies, and banking services). Due to nondisclosure policies we had to anonymize the data in the following.

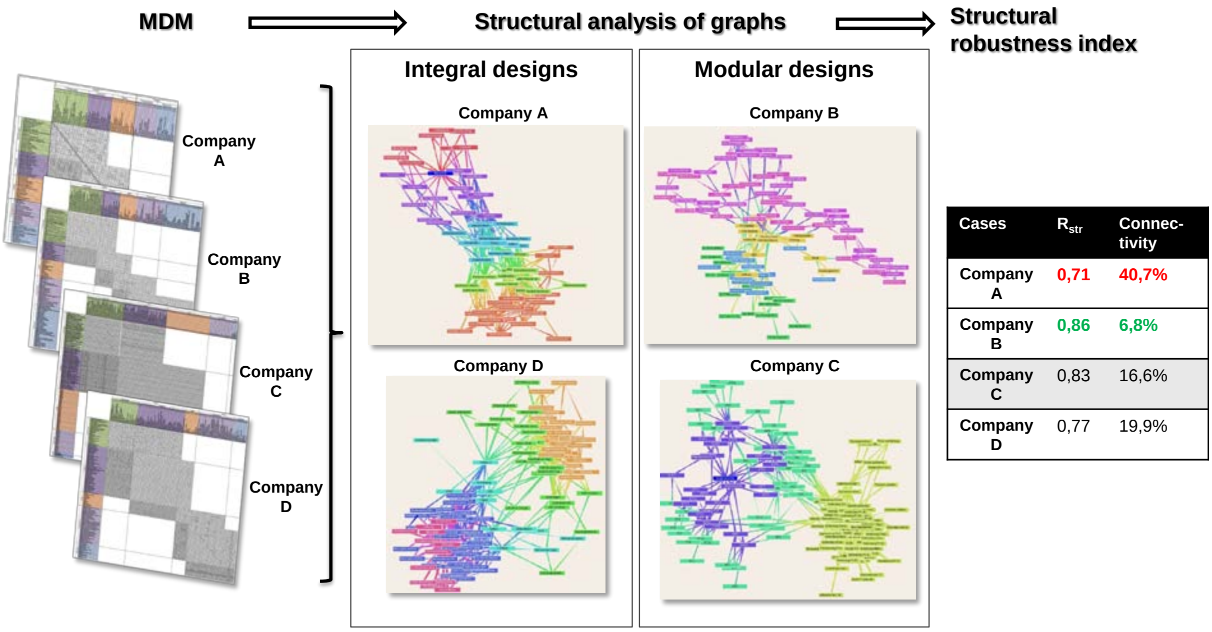
Company A is a first tier supplier in the automotive industry. They deliver chiller modules for various automotive brands. For our analysis, we choose explicitly one of their highly integrated systems which is customized and engineered-to-order. The system exhibits high connectivity of the elements within and across the domains. Whereas the system of company B to be analyzed was selected to be a highly modular system which was significantly less interconnected (the connectivity is 83% lower than in system A). Company C is a manufacturer of cashpoints. The sub-system, which was investigated in the case study, is part of a building set and fits into a wide range of systems of the offered product family. A main criterion for success of this sub-system is that it is highly adaptive to engineering adjustments but features a robust structure towards misuse. Finally, company D builds an integrated sub-module of a printing system, which is characterized by strong dependencies among parts and a high sophisticated production process. Both systems of company C and D exhibit average connectivity in comparison to the other two cases.

In order to create four comparable cases, the effort for data collection, analysis and discussion was at the same level among all partners. Each step was documented extensively to ensure reliability of the data [25]. All information was gathered and documented both in workshops with industry experts and from secondary data, i.e. proper product documentation. With the underlying research design, we ensured construct, external, and internal validity of the case study.

In the first phase, we modeled the Multi-Domain-Matrix of each product concept by incorporating relevant elements of the requirements, functions, components, manufacturing steps, and production resources domains. In these initial case studies, we qualified the dependencies between the elements simply by “0” for no dependency and “1”, if an influence is apparent. Special emphasis in these cases was given on the dependencies between product and production domains to make these interrelationships more transparent.

After in-depth discussions about the model with experts of the respective company, the calculation of the impact and the probability of each element and – finally - the condensation of the value for the structural robustness index were performed. Corresponding to their IEVs, each elements was colored respectively (green – low IEV; red – high IEV). These elements were plotted as nodes of the corresponding robustness graph (Figure 5). The results were visualized to allow further discussions in workshops with the experts.

In the final step, after elements were categorized in a Critical Elements Portfolio, quick-wins were defined individually in accordance to the particular product strategy. In ongoing work, we try to define company wise category-specific strategies for the handling of each type of elements. All steps performed in these case studies are demonstrated in Figure 5.



Cases	R_{str}	Connec-tivity
Company A	0,71	40,7%
Company B	0,86	6,8%
Company C	0,83	16,6%
Company D	0,77	19,9%

Figure 5: Overview of the results of the multiple case studies

The results support the hypotheses above. The product of Company B is highly modular and features a decoupled design. The calculated R_{str} is the highest among the investigated products. Product A is highly interconnected and integrated. Many dependencies were identified, which leads to more probable impact of changes of any kind on the structure. The product strategy behind product A is completely different to product B, which is reflected in a comparatively lower index for structural robustness. Also product C was arranged more modular. Compared to product B, its structure has a slightly minor robustness, while the connectivity among elements was significantly higher. Like product A, product D incorporates also several aspects of integral design. But the elements of product D are only half as coupled as in product A. In conclusion, we support both hypotheses: Decoupled design leads to higher structural robustness, but is not the only driver for that. Also the product modularity influences robustness positively. But there are further indicators, that robustness can also be influenced by other structural characteristics, which should be further investigated.

4 DISCUSSION

In order to forge the bridge back to the beginning of this paper, the answer to the question, how product structures can be evaluated efficiently as structural robust against emergent changes and adaptable for initiated changes, has to be scrutinized by discussing the strengths and the shortcomings of the methodology. The assessment of structural robustness can easily be carried out and even automated to some extent. It provides transparency in different aspects of the product development process – namely in concept generation in early product development, concept assessment or product improvement.

In four initial empirical case studies, we tested the methodology to assess structural robustness of different product concepts. The results were helpful for discussions with experts in industry by providing transparency and different types of visualization. The results were also useful to formulate rules in dealing with critical elements. However, the consistency of the model and the validity of the conclusions from the results are significantly dependent on the quality of model creation. The methodology focuses on inherent dependencies in the product structure. Further life phase interactions have to be investigated to improve the structural robustness of products. Nevertheless, an assessment of structural robustness as presented in this paper can support the engineering work of many kinds. We found that *AStRo* methodology supports sustainably:

- …the improvement of the product architecture
- …the reduction of change effort
- …the engineers' and management decision making process
- …the systematic deduction of design guidance
- …the continuous improvement of change projects

Another advantage of the methodological concept itself is that the degree of analysis can be adjusted to the engineers' needs in the respective development phase. The more details about the properties of the product structure are required, the deeper the analysis can be conducted

Of course, some shortcomings have to be named and some implications for further research should be addressed. The concept of *probability* was kept simple and easy to compute in order to support engineers in early phases with little effort. However, the occurrence of both emergent and initiated changes could also be estimated by applying scenario technique. While this method might cause further effort, the insights resulting from it would support superiorly the decisions made in the definition of a robust product structure. Scenarios of planned changes can be derived, e.g. from innovation strategies or – if more details are available – from milestone plans of the change management (planned face-lifts, upgrades etc.). Scenarios of unforeseen changes could be evolved likewise in a Failure Mode and Effect Analysis (FMEA) [9].

The methodology could be further enhanced by replacing static relations between elements with functional dependencies. This could be complemented by logical operators ("AND", "OR", "XOR") to refine cause-and-effect-chains of changes. The cost of changes could be attached to the weighting factors defined in this paper, like it is proposed by Clarkson et al. [4].

Four case studies proofed the practicability and the additional value for development work in practice, but the sample is still limited and should be enlarged in additional studies. The rigor of the methodology should be further substantiated. In ongoing work, more cases of additional product samples are tested. Admittedly, overlapping structural phenomena impede the distinction of different drivers for structural robustness. Therefore, we create a sample of generic structures, which enable us to investigate insulatedly the influence of certain structural significances, e.g. clusters, hierarchies, feedback loops besides others. Also the robustness of classical product architectures can be examined like slot-modular, bus-modular, sectional-modular or mixed structures [22, 23].

5 CONCLUDING REMARKS

To conclude this paper, some of the key findings should be summarized. Based on methodologies of complexity management and change propagation, we developed a methodology to assess structural robustness of product concepts. Within the methodology it is described how to model the system, calculate the impact and probability of an element to derive an index for structural robustness. Several methods for visualization and further analysis were presented. The methodology was tested in four industry cases. It was found that the assessment of structural robustness supports sustainably, amongst others, the improvement of the product architecture, reduction of change efforts, decision making in development processes, and systematic deduction of design guidance.

For future research, we suggest to refine the concept of probability, consider dynamic behavior of product concepts, and to define a set of generic test cases to confirm new algorithms in a standardized and rigor way.

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