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EVALUATING THE STRUCTURAL COMPLEXITY OF A PRODUCT FAMILY

N. E. Rissanen, J. Malmqvist and A. J. Pulkkinen

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1. Introduction

Introducing improved products is essential for many companies in order to stay competitive. Often, improvements are triggered by customer feedback but also engineers may develop solutions which improve the reliability, usability or safety of the product. However, implementing a new solution in a product or in a whole product family is not an easy task. In many cases, the consequences of the implementation have not been considered in sufficient detail in the early phase of the design. This can cause costs and problems in the later phases of the product development and the product life-cycle.

Implementing a new feature or solution into a product family can increase complexity in different systems. This can be considered a problem. Especially, increased complexity in production systems is seen a negative issue because it causes costs. Therefore, the reduction and avoidance of complexity are the design strategies for coping with the complexity in product development. [Lindemann et al. 2009]

Evaluating the level of complexity in systems has been researched in several studies. Often these studies have been based on existing systems with specific data, e.g. Suh's [1990] mapping of the interactions between different domains. More qualitative methods for evaluating the data have also been developed, e.g. Novak and Eppinger's [2001] connection measures between complex products and supply chain. However, these methods are also valid in the later phases of product development where the design data is more detailed.

The goal of this paper is to study, how does a change affect the *structural complexity* of a varying product family and how can that effect be evaluated in the early phase of a design process? The term 'early phase' indicates that detailed design has not been completed and the possible solution strategy has not been decided yet. The scope of this research is variant design and configurable product families. Two research questions have been formulated:

- RQ1: Which criteria should be used to evaluate the structural complexity in a varying product family?
- RQ2: What is the applicability, benefits and limitations of Pugh's concept evaluation matrix when evaluating structural complexity of a product family?

The research follows Design Research Methodology (DRM) by Blessing and Chakrabarti [2009]. It consists of research clarification (RC) where the literature review about complexity and product concept evaluation methods was done, and the criteria to complexity evaluation was defined. In descriptive study I (DS I), data about the current situation was collected, and the support, i.e. the method to evaluate the structural complexity in a product family, was developed and initially tested through a case study.

Chapter 2 reviews the literature on the topics of structural complexity and product family complexity and a short description of Pugh's [1996] concept evaluation tool. In Chapter 3 is represented the method of evaluating the structural complexity of a product family. Chapter 4 describes the case study, where the evaluation method is tested. Finally, Chapter 5 presents the discussion and conclusions about the usability and reliability of the used method.

2. Theoretical background

This chapter discusses structural complexity, what it means in different systems, and how it can be observed in a varying product family. At the end of the chapter, the concept evaluation and selections methods are presented.

2.1 Complexity

Several researchers have attempted to define the term *complexity*. Often, complexity can be observed from the systems behaviour. Earl et al. [2005a] state that complex systems behave dynamically i.e. the behaviour of the system cannot be predicted in certain use cases. How dynamically the system behaves is related to the system's structure. Often, complexity related to the product structure is defined by the number of elements and the relations between them. For example, Wyatt et al. [2011] introduced the complexity metrics for design, i.e. D-complexity of an architecture, which can be defined by connections and components.

The complexity related to the elements and the connections between them is called *structural complexity* [Earl et al. 2005a], [Lindemann et al. 2009]. A system structure can be either hierarchical tree structure or lattice structure [Earl et al. 2005b]. In a lattice structure the connections compose loops, i.e. closed impact chains [Lindemann et al. 2009], where a change or any kind of input may cause an avalanche of (internal) effects leading to chaos [Earl et al. 2005b].

Also Pugh [1996] has stated that complexity is related to the number of parts and interconnections but he also linked variety in this context the number of different parts and the number of functions, to his complexity definition. Variety is seen as an important characteristic of complexity, because variety among a system indicates more elements and interaction between the elements [Lindemann et al. 2009]. Variety related complexity can originate from two types of sources: internal and external sources [Elgård and Miller 1998], [Lindemann et al. 2009]. External complexity (or variety) is observed by the customers, e.g. the different variants and features from which the customer can choose. Internal complexity (or variety) is seen inside the company in e.g. the different tools, machinery and technologies that the company uses to produce the varying products [Elgård and Miller 1998].

Lindemann et al. [2009] state that complexity is not only limited to product structures but also other domains and disciplines such as processes and people who work in the company. Therefore, complexity can be divided into four different aspects: product, markets, process and organisational complexity (figure 1).

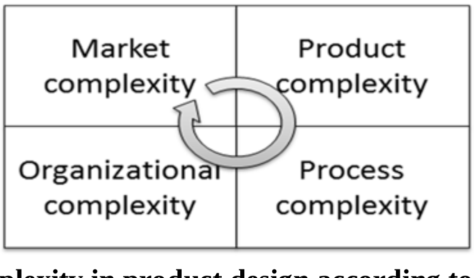


Figure 1. Aspects of complexity in product design according to Lindemann et al. [2009]

In figure 1, the aspects of complexity have been presented in a table where the arrow shows how the complexity propagates to different domains. Complexity is triggered mainly from the complexity of markets i.e. the different customer needs that the product needs to fulfill. However, complexity emerges from all these aspects. Market complexity has an influence on the complexity of the products and the product has impact on complexity of processes. Finally, the process complexity generates complexity at the organizational level when different tasks require more management and workers. The structural complexity indicates different things in different domain. [Lindemann et al. 2009] Below is explained how complexity is seen in different domains:

- Market complexity: e.g. the diversity of clientele, standards, norms.
- Product complexity: e.g. product programs or variants, technology, functionality
- Process complexity: e.g. multi-disciplinarily, development time.
- Organisational complexity: e.g. people involved, organisations, such as varying suppliers [Lindemann et al. 2009].

Market complexity possesses external complexity and product, process and organizational complexity possess internal complexity, but only internal complexity can be actively managed [Lindemann et al. 2009]. Mass customization [Pine 1993] is one of the strategic solutions which facilitate the management of the internal complexity of the varying product families.

In this paper, the term ‘complexity’ refers to the definition of structural complexity. Because complexity is related to the structure of a system, i.e. the elements and their interactions, every system possesses complexity on some level. In this paper, organisational and process domains have been excluded and the main focus is on the product complexity, especially complexity of varying product family, and market complexity.

2.2 Evaluation methods for product concepts

A product concept is defined as a rough description of the technology, working principles, and shape of a product [Ulrich and Eppinger 2003]. Evaluating the eventual success of a concept can be difficult, because of the concept’s approximate nature. The purpose of concept selection methods is to help designers to compare and choose the promising concepts for further development or refinement [López-Mesa and Bylund 2011]. According to López-Mesa and Bylund [2011], designers prefer methods which are not too complicated to use and follow but which also suit the engineering mindset. Often, the evaluation of concepts in the early phase design process is done by comparison because of the high abstraction level of concepts.

One of the frequently referred concept selection tools in product development processes is Pugh’s [1996] concept evaluation matrix [Ulrich and Eppinger 2003]. In this paper, Pugh’s concept evaluation matrix was chosen as the evaluation tool because it is relatively easy to use. It is also suitable for evaluating abstract designs and several concepts at the same time [López-Mesa and Bylund 2011]. In Pugh’s matrix, the concepts are evaluated against a reference concept with an easily accessible better-or-worse-than comparison. The evaluation criteria may vary but often they are based on customer needs. The concepts and criteria are listed on a matrix, where one of the concepts is chosen to be the reference concept, i.e. the datum, to which the other concepts are compared. The comparison is done by giving the concepts relative scores: plus (+) is better than the reference concept; minus (-) is worse than the reference concept; and (S) is the same as the reference concept. After the comparison, the scores are summed and added together, and ranked so that the concept with the highest scores is the number one and so on. [Pugh 1996]

3. A method for evaluating structural complexity of a product family

The effects of solution implementation on structural complexity were evaluated using a four step method, which is described in this chapter. This method is based on Pugh’s concept selection [1996] which is also described for example in [Ulrich and Eppinger 2003].

Step 1. Finding alternative concepts: In the first step, alternative concepts are defined. Different concept generation methods described in literature can be used. For example, Ulrich and Eppinger [2003] have presented a structure method to find concepts. However, concept generation does not always require a structured method because the engineers are used to solve problems and generate solutions during the product design. Therefore, concepts can be found in different situations, e.g. during an interview. The output of the first step is a list of different concepts which describes how the solution can be implemented into the product family.

Step 2. Formulating the evaluation matrix: When the solution concepts are identified, the datum (or reference) level is decided. According to López-Mesa and Bylund [2011], the datum should be chosen carefully because it has a significant influence on the success of the used method, and they suggest that the current solution in the market could be a good datum. The matrix is formulated so that the concepts are listed as column headers and the evaluation criteria are listed on the rows. The comparison criteria are collected from the complexity literature [Lindemann et al. 2009], [Wyatt et al. 2011]. The output of the second step is the matrix with the criteria, concept solutions and datum.

Step 3. Evaluating the effects on structural complexity: The evaluation is executed by comparing every criterion against the datum level in order to get the relative score. Because the aim is to minimize structural complexity, the relative score is assessed, so that plus (+) is less complex, minus (-) is more complex, and (S) is unchanged complexity. In order to clarify the reasons of the relative score, a short description about the evaluation can be written in the intersection of the criteria and the concept solution. In this phase, the evaluation requires understanding the product family, its variety and structure. When the relative scores are given, the score are summed and ranked from the best (number 1) to the worst (the number of the concept solution and datum). In summing phase, the possible weighting of scores needs to be considered.

Step 4. Analyzing the results and selection of the concept: When analysing the results of the evaluation matrix, the effects of structural complexity need to be understood. The best rank in the evaluation matrix does not directly indicate the final decision, but the results need to be mirrored against the goals of product development. For instance, increased complexity in a product family causes problems in maintaining the product platform.

4. The case study: The measurement instrument product family

In this chapter, the evaluation method is tested in a case study. The case study was carried out in one company in Sweden during a doctoral student exchange period. The case company is a manufacturer of process measurement instruments (PMIs). The focus of this study was on a configurable and varying product family in which the company had developed a new solution. The company wanted to see how the implementation of the solution could affect the complexity of the product. The data about the product, product family and the new solution was collected from interviews with the designers and the product specification documentation such as manufacturing drawings. During the interviews, four different strategies to implement the solution into the product family came up.

4.1 The product family and the new solution

The case company is a manufacturer of PMIs which are used to determine process variables in a tank, such as filling level, temperature and pressure. In the case product, measuring is based on contact measurement. It is used in different tanks in industries such as chemical, food and beverage, life sciences, metal and mining, oil and gas, power, pulp and paper, water and waste, and refining. The structure of one product variant is relatively simple because the number of parts is low and the linkages are mainly mechanical. Although one variant did not possess high complexity, the wide variety of the parts increases the total number of parts in the product platform on high level and generated higher structural complexity among the product family. Figure 2 is a picture of a variant of the PMI product family.

Figure 2 presents the main parts of the product family and some examples of which aspects affect the variety. The head, i.e. the measuring device, was excluded from the study because it is assembled in a different line and the solution was not seen to have an effect on it. The PMI is designed to work in different conditions, like in high temperature and pressure, and difficult circumstances in the tank, e.g. turbulent, explosive or toxic conditions, which have an effect on the type of the seal and probe. Also the connection surfaces of the device are suitable for different types of tank connections. Because of the high number of different use cases and conditions, the product family has been designed to be configurable and it possesses high variety. For instance, there are approximately one hundred different tank connection flanges available.

The new solution was represented in the patent documentation. More information about the solution was collected in an interview with the developer of the solution. The possible implementation strategies of the solution were discussed with the design engineers. According to the interviews, the company could see several benefits by implementing the solution into the product family, such as improved product durability and more accurate measuring results. The new solution could replace the old solution as a new version or revision, so that it would be a substantial improvement for the PMI product family. The problem was that would the new solution make the product family more complex than the old one? Assessing the possible effects of complexity was challenging, because the design level of the solution was in an early phase. The principle of the solution was developed but ideas on how the implementation should be executed had not been completed.

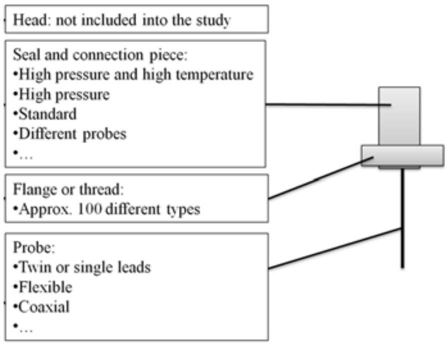


Figure 2. A variant of the PMI product family and examples of its variation, and simplification of the product's structure

4.2 The implementation strategies

Based on the interviews and data collection, four different implementation strategies were identified and, based on them, four concepts were developed. These strategies were an add-on part, a new variant, a replaceable variant and implementation into the whole product family. The principle ideas of these concepts are presented in the figures 3.

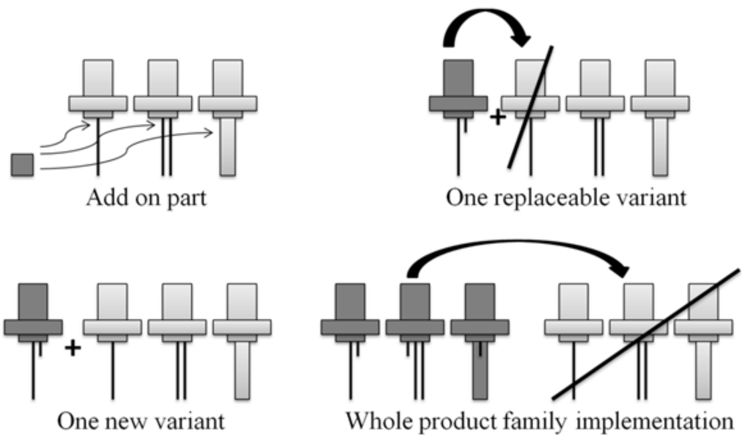


Figure 3. Four different concepts how to implement the solution into the product family

- **Add on part:** The solution is implemented into the design with one or two extra parts. It should be possible to implement the part into all product variants corresponding to a module-type solution where the interfaces are standardized. This concept would not change the externally observed variety.
- **A new variant**: The solution would be implemented into the product family by creating a new product variant and all the old designs would be stay unchanged and nothing is removed. Customers would have one new option to choose from.
- **Replace an old variant:** The solution would be implemented into a new variant which should replace one of the old types of variants. Customers would not see changes in the product portfolio, only one of the products would be improved.
- **Whole product family implementation:** The solution would be implemented into all the products in the product family. The customer would not basically see changes in the product portfolio, other than improvements in the design.

4.3 Evaluation matrix for structural complexity of PMI product family

The comparisons of different design concept were based on Pugh's [1996] concept evaluation matrix. Structural complexity was evaluated from the market and product points of view. Market complexity was also taken into account in order to see would the concept have an effect on external complexity. The product complexity aspect was further divided into two aspects, i.e. a single product complexity and product family complexity because the effects on a single product and a whole product family were different. The evaluated criteria were the number of elements and the linkages between them. In the product family, also the number of functions was noticed. The explanation of the score is clarified under the score.

The existing product family was chosen to be the datum level because the goal of the comparison was to find a concept which is less complex than the existing product. The evaluation matrix of the structural complexity of this case with four different concept and evaluation criteria is presented in table 1.

Table 1. Comparison of the different concepts against the complexity aspects

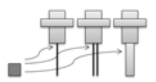
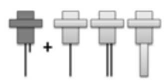
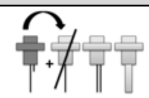
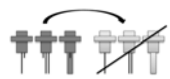
	CONCEPT				
	Existing solution (Datum)	**Add on part/module**	**A new product variant**	**A replaceable variant**	**Whole product family implementation**
CRITERIA					
Market complexity					
Number of variants offered to customer.	0 DATUM	-/0 If the add on part is suitable for every product, market complexity stays same. If not, it will increase.	- The number of offered product variants increases.	0 The number of offered product variants stays same.	0 The number of offered product variants stays same.
A Product variant					
Number of parts.	0 DATUM	- More parts in a product.	-/0/+ (parts and interactions) The effect on the new product is hard to see because the possible solution requires more detailed design. Old products will not change.	-/0/+ (parts and interactions) The effect on the new product is hard to see because the possible solution requires more detailed design. Old products will not change.	-/0/+ (parts and interactions) The effect on the product is hard to see because the possible solution requires more detailed design. Redesigning whole product family enables decresing the number of parts.
Number of interactions.		- More interfaces in a product.			
Product family					
Number of modules in the module platfrom.	0 DATUM	- More modules is needed.	- More modules is needed.	0 The number of modules or interactions will not change (If the new variant replaces totally the old variant).	0 The number of modules stays same, when the solution is in all modules.
Number of interactions.		- New interactions are required between the modules.	- The new interactions are required between the modules.		+ Solution enables less mechanical interactions between the modules (less loops).
Number of functions.		- One new function is introduced.	- One new function is introduced.	- One new function is introduced.	0 One new function is introduced, but one is also removed.
Sum	0	-6 or -5	from -6 to -2	from -3 to 0	from -2 to +3
Rank	2	5	4	3	1

Table 1 shows that the complexity of a single product family was difficult to evaluate, because of lack of details in the design. Therefore, the evaluation of a product did not give an unequivocal answer. The same problem was with the linkages between the parts. The evaluation of the number of modules or larger components was easier, because the main components would stay basically unchanged also in the new design.

The most suitable concept was judged to be the result that could give the best solution in the best case. That was is the implementation into the whole product family. The worst concept would be the solution that has the worst result that was the add-on part. However, the whole product family implementation could end up being worse than the existing solution from the perspective of complexity. Two of the concepts (add-part and a new product variant) also increased the market complexity, i.e. the external complexity, which was not pursued in this case.

5. Discussion and conclusions

This paper presented the evaluation of structural complexity of a product family based on Pugh's concept evaluations matrix in the early phase of product design. With this study we got following answers to the Research questions:

- RQ1: Which criteria should be used to evaluate the structural complexity in a varying product family?

The criteria are based on the Lindemann et al. [2009] definition of structural complexity from the aspect of product and market complexity. The product complexity is divided further into the complexity of a single product and the complexity of the product family, because they are seen as substantially different. In the case study the structural complexity characteristics are the number of modules, parts or product variants, the interactions between them, and the number of functions.

- RQ2: What is the applicability, the benefits and limitations of Pugh's concept evaluation matrix when evaluating structural complexity of a product family?

Evaluating the structural complexity of the product family with Pugh's complexity evaluation matrix in the early phases of the design is problematic. In the early phases, the structure of product is usually very abstract but the criteria require detailed information about the concept, e.g. the number of parts. The more abstract the design is, the less sure it is what the product will eventually look like and how many elements and linkages there will be in the structure. In this paper, the case study was based on the existing design, so the abstraction level was not as high as in new product development. However, the lack of details hindered the evaluation. Therefore, the results of the case study are only tentative, but they may guide the designer into a certain direction.

The history of the case company has shown that implementing a new feature into the product family has increased complexity in the product. Often, the improvements have been introduced as additions to the old design, which lead to a higher number of modules and interactions in the product. This can also be seen from the evaluation matrix where the concepts add on part and a new variant increased the complexity in the product and in the product family. According to the used method, the best solution from the perspective of decreasing the structural complexity would be achieved if the solution was implemented into the whole product family.

However, changing the entire product family is a major product development task. It would require a large investment by the company, which could be difficult with limited resources. For example, the amount of the investment depends also on the change propagation [presented e.g. Earl et al. 2005a], i.e. how many other changes one change could cause in the product. This propagation can also spread to the processes' complexity and to the other aspects of complexity. Therefore, change propagation to other systems is one of potential aspects that could be evaluated using this method in the future. Also, the method could be tested in more complex products and systems than the case product in this paper.

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M. Sc. Noora Rissanen
Doctoral Student, Researcher
Tampere University of Techology, Department of Production Engineering
Korkeakoulunkatu 6, Tampere, Finland
Telephone: +358 40 198 1757
Telefax: +358 3 3115 2753
Email: noora.rissanen@tut.fi