COST PROGNOSIS OF MODULAR PRODUCT STRUCTURE CONCEPTS

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Abstract

Modular product structures are often used by companies dealing with a high variety in their product families to cope with that challenge. Due to the gradual properties of modularity, more than one modular product structure concept is developed. The cost prognosis shown in this paper supports the selection of concepts by making the monetary effects of changing product structures transparent. It is one unit of the complexity cost management approach, which is based on a systematic literature review. The correlation of the method unit with the integrated PKT-approach is shown and compared to methods from literature. The cost prognosis is described in detail using the example of a product family of floor cleaning robots and verified by applying it on a product family of elevators. The detailed analysis of cost effects of modular product structure concepts supports decision making and leads to cost advantage solutions.

Keywords: Complexity cost, Decision making, Integrated product development, Product families, Product structuring

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1 INTRODUCTION

Companies with great variety in their product families often use modular product family structures to cope with the challenge. They use the structures to benefit from the effects of commonality, such as cost savings created by learning curve effects in production or scale effects in procurement (Ehrlenspiel et al., 2007). As modularity is a gradual property (Salvador, 2007) and more than one modular solution is possible, companies need to evaluate product family structure concepts. In decision-making, companies often focus only on production costs. Complexity costs that arise from internal variety of product families (Kruse et al, 2015) are not taken into account because companies do not know how to measure them. Current research offers a number of modularization methods with different approaches and focuses, however there is insufficient support for assessing product family structure concepts (Krause and Ripperda, 2013). The effects of modular product family structures on total costs are not known during concept selection and need to be financially quantified.

The purpose of the cost prognosis approach shown in this paper is to support concept selection by making the monetary effects of changing product family structures transparent. First, the complexity cost management approach is introduced and compared to methods from literature. Then the cost prognosis, a step in complexity cost management, is described in detail using the example of a product family of floor cleaning robots, and verified by applying it to a product family of elevators. A summary of the introduced approach, the conclusion and the outlook for further research are then given.

2 COMPLEXITY COST MANAGEMENT

Complexity cost management is an approach to predicting, assessing and reducing the total costs of product family structure concepts. It integrates the product, process and cost structure to describe the effects of modularity by combining methods and tools from product development and cost accounting.

Modular product family structures can be developed using the integrated PKT-approach for developing modular product families (Krause and Eilmus, 2011a; Krause and Eilmus, 2011b; Krause et al., 2014). The approach aims to reduce the variety of product families inside a company while offering improved variety to the external customer. It was developed at the Institute of Product Development and Mechanical Engineering Design (PKT) at the Hamburg University of Technology. The approach provides several method units for project specific purposes. The new method unit, complexity cost management, measures the monetary effects of reduced internal product and process variety, as shown in Figure 1.

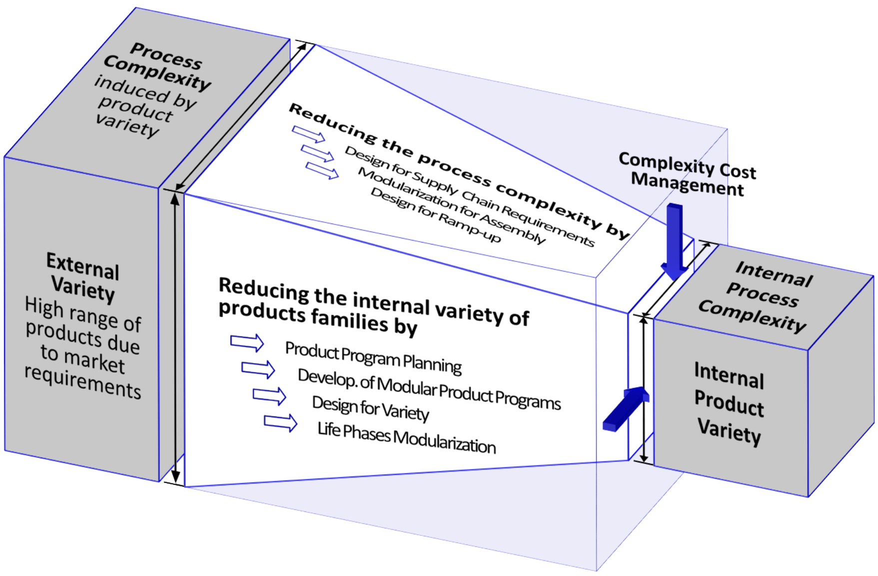


Figure 1. Complexity cost management within the integrated PKT-approach for developing modular product families (Ripperda and Krause, 2014a)

Prior to this paper, quantitative cost information was included in the integrated PKT-approach by using the average cost practice of a modularization project for wiring harnesses in forklift trucks. The results showed how the consideration of complexity costs, in terms of code number costs (indirect cost that occurs for one type of component in all life phases), can support companies in selecting modular product family structure concepts and how it can lead to different solutions to traditional cost accounting. The results also showed the limitations of the average cost practice and the need for further development of cost prognosis to understand the effects of modularity in more detail (Ripperda and Krause, 2014b). Systematic review of cost in modularization approaches demonstrated that an integrated complexity cost management approach in modular product family structure concept development should consist of a cost prognosis, cost assessment and cost reduction unit (Ripperda and Krause, 2014a). Figure 2 shows the main steps of the complexity cost management approach.

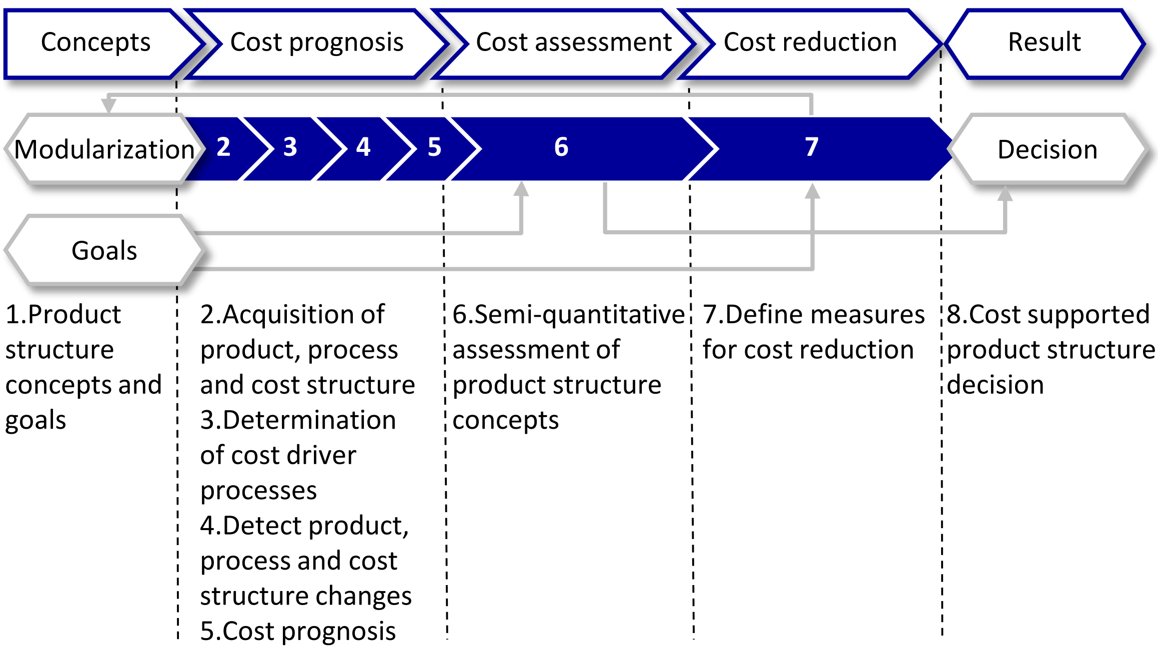


Figure 2. Overview of the complexity cost management approach

Complexity cost management starts with the acquisition of product family structure concepts and project goals; continues with cost prognosis, assessment and reduction; and finishes with output and results. At the beginning, the goals of the concepts are defined and product family structure concepts developed using the integrated PKT-approach or another modular development approach, such as the Design Structure Matrix or Modular Function Deployment (Krause and Ripperda, 2013). In the cost prognosis unit, the current product, cost and process structure are acquired. The cost driver processes are determined and product, process and cost structure changes are detected. In the last step of the unit, the relative costs of the concepts using modularity are predicted. During cost assessment, a semi-quantitative assessment, combining cost information with qualitative goals, is carried out (Vahs, 2002). Based on the cost prognosis and assessment, the final unit, cost reduction, defines measures for further cost reductions as input for possible improvement to the concepts in the modular development approaches. The last unit is based on generic effects of modularization, which can also be carried out before or during concept development to gather input for low-cost variety development, or skipped if no further cost reduction is intended. Because of the complexity cost management approach, a cost supported product family structure decision can be made.

There are related approaches described in literature that have different aims and boundary conditions, a selection of which is named. Detailed information can be found in the systematic literature review of Ripperda and Krause (2014a). One related method presents a production cost estimation framework based on an activity-based costing (ABC) system for product families (Park and Simpson, 2004; Park and Simpson, 2008). An ABC analysis is also used to estimate an economic grade of product modularity (Thyssen et al., 2006). Another approach calculates the life cycle costs of a product

program to eliminate unprofitable variants (Hansen et al., 2012). None of these approaches predicts the costs of modular product family structure concepts, which would support concept selection.
The next section describes the cost prognosis unit using the example of a product family of floor cleaning robots. The approach is applied in practice in section four, where the approach is used in a project to predict the costs of elevator car frame concepts. Future publications will introduce the steps 'cost assessment' and 'cost reduction' in detail.

3 COST PROGNOSIS

The cost prognosis unit of the complexity cost management approach aims to support concept selection by identifying the monetary effects of modular product family structures in all life phases. For cost prognosis, the product, process and cost structure of the current state, as well as the concepts, are analysed and synthesized. The relative total costs of the concepts related to internal variety, such as complexity costs, are predicted. The necessity and benefit of external variety is not examined within the approach because it is assumed that companies know their customers' needs. The approach uses several product development and cost accounting methods and tools, which are referenced but not explained in detail within this paper. Cost accounting methods calculate the current cost structure. The proposed method predicts the cost structure of modular product family structure concepts. Figure 3 illustrates the main steps of the cost prognosis unit.

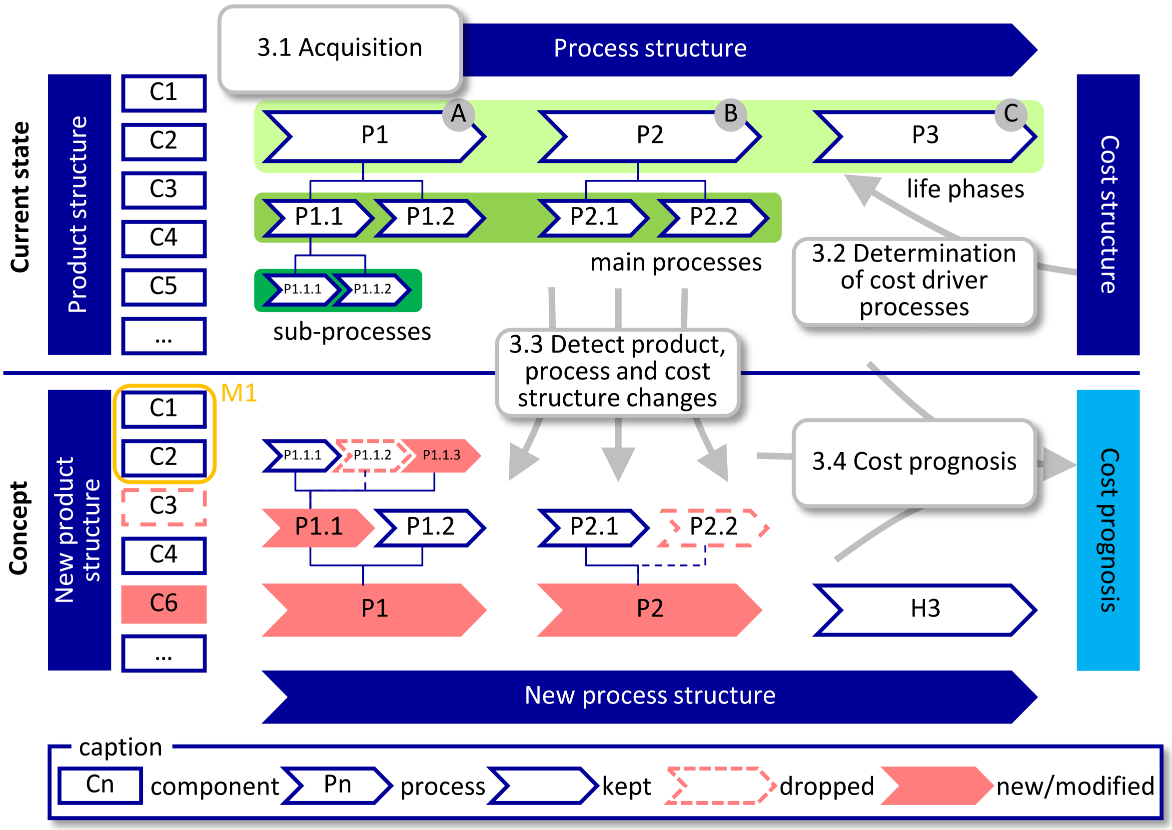
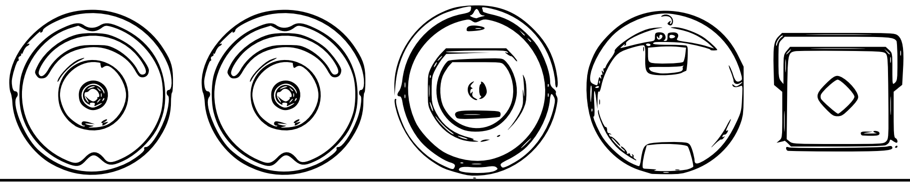


Figure 3. Cost prognosis unit

First, the structure, processes and cost structure of a product family are acquired (Section 3.1). Second, analysis of the cost structure leads to cost driver processes, which have to be analysed in more detail using the Pareto criterion (Section 3.2). Third, changes in the product family structure concepts and associated changes in the cost driver processes are detected (Section 3.3). Additionally, changes in material costs are recorded. Finally, the analysed changes and modularity effects lead to cost prognosis of the concepts based on the current cost structure (Section 3.4). The cost prognosis unit and complexity cost management are generic approaches. The cost prognosis methods need to be adapted to the applicable product family and company situation, as does every cost accounting method (Hicks, 1999).

The four steps described above will be explained in detail using the example of a product family of floor cleaning robots (Table 1). This example was used in a workshop at the International Summer School "Product Architecture Design - PAD", which took place at the Hamburg University of Technology in Germany in 2014. International researchers discussed modular product family structures and their cost effects. A comparison between the results of the average cost approach (Ripperda and Krause, 2014b) and the cost prognosis unit is also shown in Kruse et al (2015).

Table 1. Product family of floor cleaning robots



variant	SR400	SR500	SR1000	WR600	WM2000
cleaning principle	vacuum	vacuum	vacuum	scrubbing	mopping
control concept	buttons	buttons	touchpad	buttons	buttons
discharge bin sign	no	yes	yes	yes	no
dirt detection	no	yes	yes	no	no
filter type	standard	standard	HEPA	standard	-
volume per cycle	60000 pc.	50000 pc.	25000 pc.	55000 pc.	50000 pc.

The product family consists of five variants. There are three vacuum cleaning robots (SR400, SR 500 and SR1000), one scrubbing and cleaning robot (WR600), and one mopping and cleaning robot (WM2000). They each have distinct customer-relevant properties and varying volume, as shown in Table 1.

3.1 Acquisition of existing product, process and cost structure

The product, process and cost structure of a product family is acquired in the first step of the cost prognosis unit. These data should be available, documented and easily accessible in every company. Project experience indicates that, especially in smaller and mid-size companies, the information is not available and has to be recorded and evaluated to describe the state of the product family. There are several tools that support this step. The acquisition of the information for the product family of floor cleaning robots is shown in Figure 4.

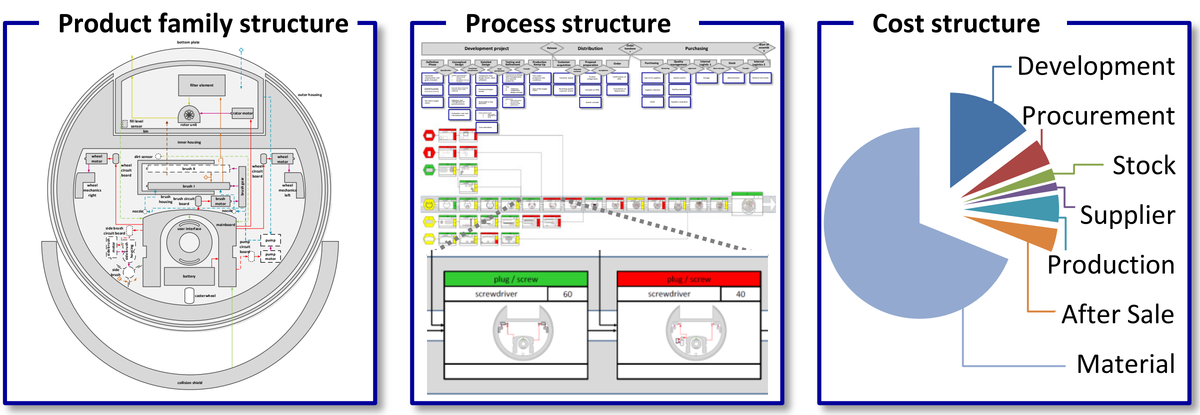


Figure 4. Acquisition of product family, process and cost structure

On the left of Figure 4, the product family is illustrated using the Modular Interface Graph (MIG) (Blees and Krause, 2008; Gebhardt et al., 2014). The MIG visualizes and analyses the variety of components and their connecting flows across the whole product family. In the middle of Figure 4, the life phase processes are illustrated as a stage gate process and the assembly process is visualized with the integrated Product and Assembly Structure (iPAS) (Halfmann et al., 2011). The iPAS combines the product family structure and the assembly process. The cost structure was calculated using three levels of cost accounting: 'cost-type accounting', 'cost centre accounting', and 'cost unit accounting' (Freidank, 2012). Cost-type accounting divides the costs into direct and overhead costs. Direct costs can be directly associated with product families. Cost centre accounting is used to allocate the overhead costs to the life phases. Completing direct and overhead costs are allocated to product families using cost unit accounting.

3.2 Determination of cost driver processes

After acquisition of the data, the cost driver processes that have to be further analysed are determined by combining the state process and cost structure. The Pareto criterion is used to make this step more efficient, as not every process has to be analysed in detail. Only the processes that contribute 80% of the total costs (without material costs) at each process level are analysed in more detail. It is assumed that a change in the internal variety has a high impact on cost-intensive processes. The other processes will not be ignored, but their processes do not have to be analysed deeply. At the main processes level, the cost driver processes are split, using Pareto criterion for analysis at a sub-processes level. If necessary, this process can be repeated to achieve the necessary granularity. For the product family of floor cleaning robots, the processes are analysed to the sub-processes level (Figure 5).

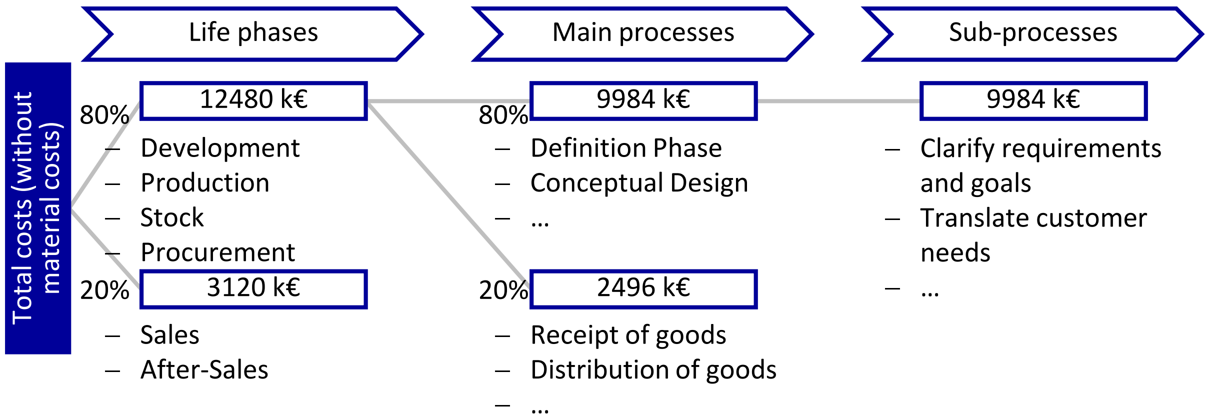


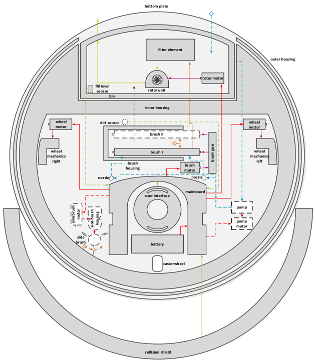
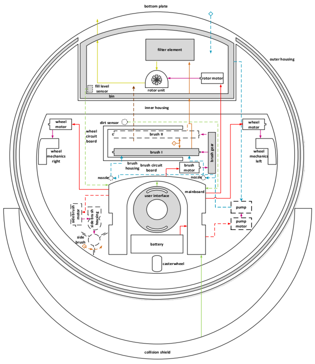
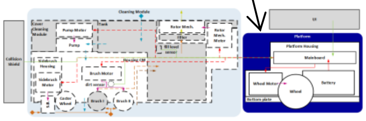
Figure 5. Identified cost driver processes using the Pareto criterion for the product family of floor cleaning robots

In this example, 80% of the total costs occur in the life phases development, production, stock and procurement. The cost driver life phases are further divided into their main processes (e.g. definition phase, conceptual design, etc) and then split again, using the Pareto criterion. The main processes of development and production need to be analysed more deeply at the sub-process level (e.g. clarify requirements and goals, translate customer needs, etc).

3.3 Detect product, process and cost structure changes

Besides the determined cost driver processes, the product, process and cost structure changes have to be detected. The three modular product family structure concepts (a, b and c) developed with the integrated PKT-approach (Table 2) or any other modularization method, such as DSM or MFD, are analysed for product family structure and resulting process changes. Additionally, the changes in concept material costs compared to the existing state are recorded.

Table 2. Product family structure concepts a, b and c illustrated using MIG

Concept a	Concept b	Concept c
Separate improvement	Combination of SR and WR	Platform for all variants
		Platform  *Lateral view*
Low level of product commonality	High level of product commonality	High level of product and process commonality

Standard component   Variant component

Concept 'a' separately improves the variants SR, WR and WM, and has a low level of product commonality within the product family, as indicated by the grey (variant) components in the MIG. Concept 'b' combines the variants SR and WR to get a higher degree of commonality. Concept 'c' proposes the use of a platform to gain a high level of product commonality. Additional to the MIG, the product family structure changes are documented in a bill of materials, which describes the components that are kept, modified, dropped or developed. This information leads to changes being required in concept processes. The effort required to change processes has to be estimated by the product experts for all life phases recorded for a particular state. Additionally, the direct costs for alternative components have to be estimated using offers, existing data and product expert estimations. The process structure changes are shown in Table 3 for concept 'a' of the floor cleaning robots product family.

Table 3. Excerpt of process structure changes in life phase development, detailed to sub-processes for time-driven, activity-based costing (TD ABC)

Life phase	Development	Current state (time in [min] per component)						Concept a (number of comp.)		
		Known		Similar		New		Known	Similar	New
		Min	Max	Min	Max	Min	Max	48	3	2
		Average		Average		Average		Total time in [min]		
Main process	1 Definition Phase	15	15	40	76	96	190	720	150	240
		15		50		120				
Sub-processes	1.1 Clarify req. and goals	5	5	16	30	40	80	240	60	100
		5		20		50				
	…	…		…		…		…	…	…

The one-time effort that depends on known, similar or new components is shown on the left-hand side of Table 3. For every process level, product experts estimate the minimum, maximum and average times. On the right-hand side, the number of known, similar and new components in concept 'a' is

listed to estimate the development effort required for the new concept, based on the average process time. For instance, the definition phase in development takes an average of 50 minutes for similar components. The developed concept 'a' contains three similar components. These similar components will take about 150 minutes to be defined. This forms the basis for the TD ABC method for identified cost driver sub-processes. These changes have to be estimated for all processes in the state, with specificity depending on the identified cost driver process level.
The detection of product and process changes can also be done during product, process and cost structure acquisition, when only considering the affected processes and reducing the effort of data collection and evaluation. This simplification has the disadvantage that the costs of later developed alternative concepts cannot be predicted, due to current state cost information gaps. Additionally, cost driver processes may not be detected.

3.4 Cost prognosis

The cost of the product family structure concepts can be predicted, based on the identified product, process and cost structure changes, the chosen cost structure and product expert estimates.
Different calculation methods are used to predict production and overhead costs for the concepts at the process level. For sub-processes, the resource-based, time-driven, activity-based costing is used (Kaplan and Anderson, 2007). In TD ABC, the sub-processes are measured in time, and are estimated by the product experts. At the main process level, activity-based costing of complexity indicators is applied to predict costs (Meier and Bojarski, 2013). In this approach, the complexity indicators 'number of components', 'number of variants' and 'number of process steps' are used. At the life phase level, the costs are distributed equally among the products. Effects of modular product family structures, such as learning curve effects in production or scale effects in procurement, are considered. Results for the floor cleaning robot product family concepts are shown in Table 4.

Table 4. Relative costs per life phase, production (PC) and complexity (CC) costs for floor cleaning robot product family concepts a, b and c, compared to base state (100%)

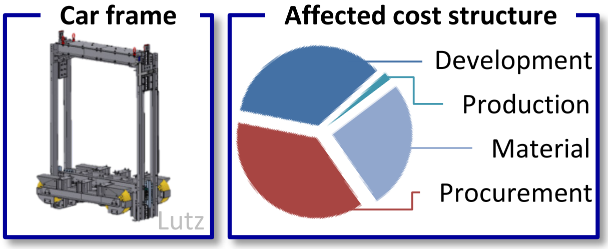
	Development	Procurement	Stock	Production	Material	PC	**CC**
a	103%	91%	96%	90%	99%	98%	**97%**
b	104%	74%	90%	89%	98%	97%	**94%**
c	105%	73%	88%	75%	95%	93%	**89%**

Production costs are also listed in the table because they are an important KPI for companies. The current cost structure shows that material and development are the main cost centres (Figure 4, right-hand graphic). An increase in cost is predicted in development, because new components have to be developed. A decrease in cost is predicted in procurement, stock, production and material due to scale effects of commonality. In this example, a reduction of production and complexity costs is shown. A reduction of up to eleven percent in complexity costs is predicted by raising commonality in the product family of floor cleaning robots. A solely quantitative assessment would suggest the selection of concept 'c' to achieve best results.
The relative savings are small in this example. Additionally, the results in Table 4 simulate a higher accuracy than is actually achievable with this approach, because of product expert estimates and the difficulty in accounting for all effects of modular product family structures. Uncertainties compared to predicted savings might be too small for companies to change their existing product family structure.
The results are generated during the concept phase to support product family structure concept selection. This approach is not designed to support controlling or sales. It would be possible to predict the cost of individual variants using the cost prognosis unit, but this is not the focus of the approach, because product family structure concepts must be considered in total.

4 COST PROGNOSIS OF ELEVATOR PRODUCT FAMILY STRUCTURE CONCEPTS

The cost prognosis unit is used in a joint research project with LUTZ Elevators, a medium-sized enterprise. The project, called ModSupport (Krause et al, 2015), aims to develop a modular concept of an elevator product family. The company specializes in bespoke onshore and offshore elevators. The

resulting low quantity and high internal variety lead to large efforts in development, long lead times and high failure rates. The goals of the project are to use modular product family structures to raise the level of commonality within a product family and decrease complexity costs.
Two product family structure concepts for elevator car frames were developed using the integrated PKT-approach and compared to the existing state using the cost prognosis unit. In concept x, a high level of product commonality was sought. Concept y was developed to be implemented rapidly in the company and has a lower commonality. For the cost prognosis, life phases development, procurement and production, and material costs were considered. The results are presented in Figure 6.



Cost prognosis

	Dev.	Proc.	Prod.	Material	PC	CC
x	34%	66%	75%	88%	87%	**75%**
y	62%	70%	89%	95%	94%	**89%**

Figure 6. Results of the cost prognosis of the elevator product family structure concepts, including production (PC) and complexity (CC) costs

The existing cost structure of the elevator car frames shows the costs, the life phases affected by the product, and process changes in the concepts x and y. The greatest impact of the new product family structure is on development and procurement. Material costs make up 25 % of the affected costs; impact on production cost changes is negligible. In this case, the use of modular product family structures leads to a decrease in development and procurement costs, and results in complexity cost (CC) savings of 11 % in the short-term, and up to 25 % in the longer term. The reduced recurring development effort has a much higher effect on costs than the one-time effort of developing the modular product family structure. Scaling effects decrease procurement and production costs by using standard components. The effect on the production processes is small, because they change only slightly.
Even though not all cost data were available, significant effects of modularity on costs could be shown. The generic approach of the cost prognosis unit has to be adapted to the product family and company situation. This practical example from industry better demonstrates the potential of the approach than the theoretical example in Section 3.

5 CONCLUSION

The cost prognosis shown in this paper supports the selection of modular product family structure concepts. It presents besides cost assessment and cost reduction a unit of the complexity cost management approach. Considering overhead costs alongside production costs lead to different product family structure solutions. Transparent and effort-reducing cost prognosis supports product developers during concept development.
The complexity cost management approach, based on the literature, was introduced before correlation with the integrated PKT-approach was demonstrated. Preliminary studies on costs and modularity were described and related approaches from literature listed. Next, the steps of the cost prognosis unit were described in detail using the example of a product family of floor cleaning robots. The results of the effort-reducing approach showed detailed cost information about the effects of the modular product family structure concepts. Advantages and limitations of the approach were discussed. The cost prognosis unit was verified using the example of elevator product family structure concepts. Necessary adaptations, approach feasibility and results in practice were presented. Detailed analysis of the cost effects of modular product family structure concepts supports decision-making and leads to cost advantage solutions.
Further research is needed to verify use of the cost prognosis unit for other product families and companies. Uncertainties in the prognosis also need to be considered. The approach will next be applied to the development of a modular entrance area of an aircraft. Additionally, the interaction of cost prognosis, cost assessment and cost reduction within complexity cost management will be analysed.

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