INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

HOW TO GENERATE DESIGN RULES FOR COST-EFFICIENT DESIGN OF MECHATRONIC PRODUCTS

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ABSTRACT
This contribution presents special requirements necessary for the cost-efficient design of mechatronic products. A generic target costing guideline with integrated auxiliary design rules is introduced as one appropriate approach towards supporting multidisciplinary product development processes.
However, in order to set up design rules according to the classic mechanical engineering model, first sound knowledge about the cost origin of mechatronic products must be attained.
A design study was developed and a data base of exemplary mechatronic products across different industries was gathered for analyzing connections between structural product complexity and the resulting product costs.
The analysis results in product-spanning conclusions for individual products, in addition to prospects for the derivation of first order design rules for the cost-optimized design of mechatronic products.

Keywords: Mechatronics, complexity, costs, empirical studies

1 INTRODUCTION
Mechatronics consistently finds its way into the products of classic mechanical engineering and with this, this field opens potential for success by the employment of new principle solutions [1, 2]. Thereby, the primary goal is mostly the optimization of a mechanical basic system in terms of the provided functionality. This is reached by the integration of working principles of other technical disciplines [1, 3]. So for example the enhancement from classical to digital photography brought with it far more than merely a change in the storage medium from film to CCD chip. Contrary to the mechanical camera, with which the diaphragm, exposure time and image definition take place manually, the mechatronic system can gather information from the environment over appropriate sensors and adjust the necessary settings independently. This is reached through the replacement of mechanical connections between the individual elements by means of electronic/information-technical connections. From the electronic signals provided by the sensors, the data processing determines the most favorable settings in the current situation with the help of the algorithms implemented in the software and provides the signals for the different drives [3, 4].
Consequence of the resultant multidisciplinarity is an increased complexity of mechatronic products in comparison to classic mechanical products. Complexity in the presented context describes the structural complexity, which results from the number and diversity of the components and their relations [5].
A rising product complexity in turn leads to an increased process complexity [6]. In order to meet the risen demands of mechatronic products in view of their development processes numerous procedural models, methods and tools have been developed over the last years.
With this trend of “multidisciplinarization” however, the cost management and especially the target costing of mechatronic products has been neglected. Just as with the already mentioned aspects of the development and handling of mechatronic products increased demands also arise here [7].
Though numerous approaches for cost estimation and optimization of discipline-specific product shares exist in the individual disciplines, one hardly finds discipline-spanning approaches for mechatronic overall systems. However, to early account for costs of test and integration for example, which make up a considerable amount of production costs, such approaches are indispensable [7]. Without the presence of such approaches the overview is missing over the cost origin of mechatronic concept alternatives, which hinders an effective “design to cost”.

2 PROBLEM DESCRIPTION

To set up the requirements of a methodical support of the target costing of mechatronic products several interviews with engineers from industry have been conducted and a questionnaire based study has been evaluated [6]. From that several requirements regarding *information handling*, *cost analysis* and *cost optimization* could be deduced [11].
In order to meet these requirements a framework based guideline has been set up. Core to this guideline is a generic procedural model of the target costing process. The procedural model is made up of several process modules representing single process steps (light grey arrows in Fig. 1). Linked to every process module are auxiliary means (hexagons in Fig. 1) that offer support in the according design situation.

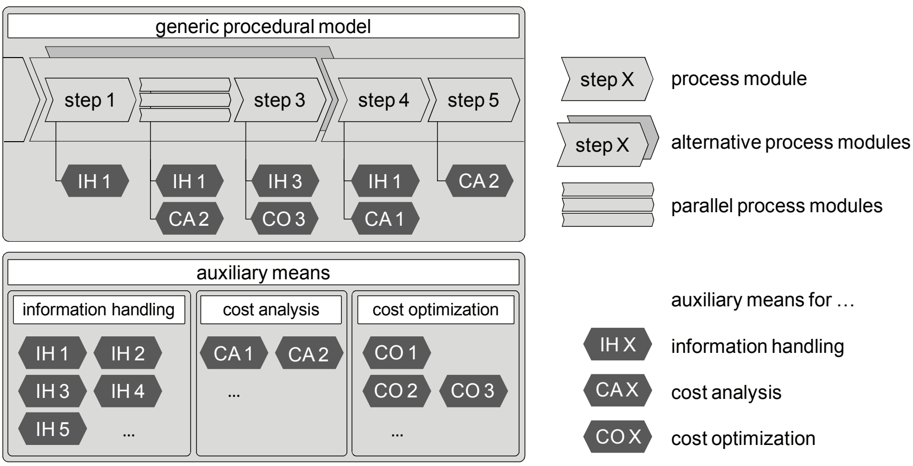


Figure 1. Structure of the developed target costing guideline: Generic procedural model with linked auxiliary means for the information handling, the cost analysis and the cost optimization

Exemplary auxiliary means that have already been set up are for example a set of cost estimation methods that help to estimate discipline-specific and -spanning cost shares.
In order to support the process of *cost optimization*, it is the goal to provide, among others, appropriate design rules for the cost-optimized design of mechatronic products. However, there are some problems with the formulation of design rules that have to be solved first: The available knowledge about the relation between a product's characteristics and its costs is far more developed in classic mechanical engineering than in mechatronic engineering. In mechanical design there are numerous guidelines for cost efficient design [8]. These are concerned with the cost optimized detailing of specific component properties such as for example the positioning of weld seams or the selection of material [8, 9] (Fig. 2).

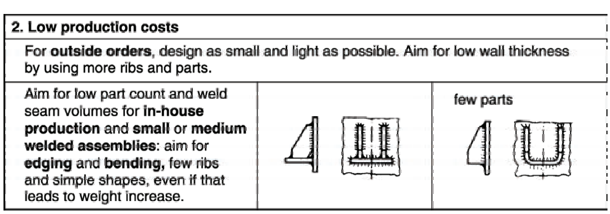


Figure 2. Exemplary design rules for the cost-optimized positioning of weld seams [8]

These characteristics are still important for mechatronic products but do no longer play the leading part. Drawing conclusions solely on product costs by analysis of separate component specifications is not expected to work for multidisciplinary products with strongly interlinked components.

The author's preliminary work suggests that the product structure with its underlying structural characteristics cannot be neglected due to its direct effect on cost saving potential [10, 11].
However, consolidated findings about the relation between characteristics of a product's structure and its cost structure have not been documented so far. Consequently there are no guidelines for the cost efficient design of the product structure – especially in the sense of cost efficient partitioning – of mechatronic products.
In order to meet this shortcoming, extensive analyses with existing products have been carried out. Therefore a study had to be developed, including factors such as the definition and analisis of product characteristics, measures, structural elements and cost shares. Then a suitable data base which spans mechatronic products over various disciplines and price ranges had to be put together. Besides, the products should range in the area of smaller to middle numbers of items produced and either exist of functionally well separable assemblies or show from the start a manageable number of system components. Moreover, a comparable level of detail had to be assured concerning the product data as well as the cost data.
After the isolated processing and examination of the investigation objects general conclusions and correlations could be examined. On this basis design rules can be deduced and then be integrated into the described "design to cost" guideline for mechatronic products.
In the following the data base and fundamental data preparation are presented, so that in the consequence the accomplished analyses can be stated and the study design be explained by means of a simplified example.

3 ANALYSED DATA BASE

The study's data base described here consists of nine assemblies and overall systems from a total of four German enterprises in the plant engineering and the capital goods industry. Figure 2 shows the investigation objects and their characteristic features in the overview:

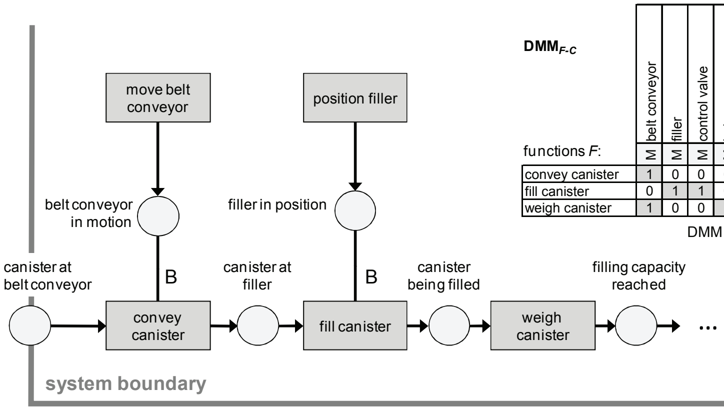
Enterprise	Sector / numbers of items	Object	number of functions	number of components	cost range
Enterprise A	capital goods industry; middle numbers of items	A1	5	13	8H
		A2	16	25	5H
		A3	32	13	8H
		A4	3	9	9H
Enterprise B	plant engineering; small numbers of items	B1	4	15	15T
		B2	9	19	7T
Enterprise C	plant engineering; small numbers of items	C1 (overall system)	22	47	91T
Enterprise D	capital goods industry; middle numbers of items	D1 (overall system)	11	20	3H
		D2 (overall system)	11	20	4H

H hundred Euros
T thousand Euros

Figure 3. Overview of the data base

3.1 Preparation of the Product Data

To make the investigation objects and their data material comparable, a suitable way of data processing had to be found that generated a comparable picture of the structural characteristics and the complexity of the systems analyzed. Thereby both functional and physical dependencies should be illustrated and examined. For this purpose the available systems are at first described with a flow oriented functional model (fig. 4 left) [12]. This type of functional modelling was chosen as definite flows can be assigned to every system. Then, on the basis of the functional model, solution-neutral partial functions of the systems which in sum describe the overall functionality of the systems are identified.
The partial functions were assigned to the system components by means of a Domain Mapping Matrix (DMM [13]) (fig. 4 right). Before, the considered system components had to be won from the parts lists available to the respective systems. Thereby it was to be considered that the resulting system components are of comparable granularity despite the deviating degree of detail of the original data.



$DMM_{F\text{-}C}$ — components *C* with classification:

functions *F*:	belt conveyor (M)	filler (M)	control valve (M)	balance (M)	servo drive (A)	filler drive (A)	evaluation electronics (LE)	drive control (S)	flow control (S)	fill control (S)
convey canister	1	0	0	0	1	0	0	1	0	0
fill canister	0	1	1	0	0	1	0	0	1	1
weigh canister	1	0	0	1	0	0	1	0	0	1

DMM Domain Mapping Matrix

Figure 4. Flow-oriented functional model of a filling system (extract) and allocation of functions and system components via $DMM_{F\text{-}C}$

On the basis of the DMM-based allocation of sub functions and system components the linkage of system components due to their common fulfillment of one or more functions can be calculated and illustrated in form of a Design Structure Matrix (DSM [14]) using the following equation [15]:

$$DSM_{C(F)} = DMM_{F\text{-}C}{}^{T} \bullet DMM_{F\text{-}C} \qquad (1)$$

The linkage information of the DSM can be illustrated alternatively in a strength-based graph (fig. 5 right) [16]. As shown on the following pages this representation enables a faster recognition of (cost) relevant structural characteristics.

$DSM_{C(F)}$

	belt conveyor (M)	filler (M)	control valve (M)	balance (M)	servo drive (A)	filler drive (A)	evaluation electronics (LE)	drive control (S)	flow control (S)	fill control (S)
belt conveyor	2	0	0	1	1	0	1	1	0	1
filler	0	1	1	0	0	1	0	0	1	1
control valve	0	1	1	0	0	1	0	0	1	1
balance	1	0	0	1	0	0	1	0	0	1
servo drive	1	0	0	0	1	0	0	1	0	0
filler drive	0	1	1	0	0	1	0	0	1	1
evaluation electronics	1	0	0	1	0	0	1	0	0	1
drive control	1	0	0	0	1	0	0	1	0	0
flow control	0	1	1	0	0	1	0	0	1	1
fill control	1	1	1	1	0	1	1	0	1	2

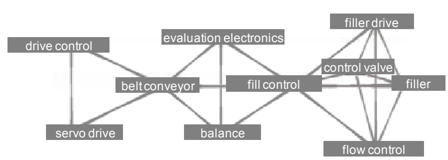


Figure 5. Functional component structure; in form of as $DSM_{C(F)}$ and the associated strength-based graph

Apart from the functional linkage of the system components, also their physical linkage through flows of forces, signal, energy or material is of interest for the accomplished analyses. This information is also modeled in form of a DSM and a strength-based graph (fig. 6).

$DSM_{C(C)}$	belt conveyor	filler	control valve	balance	servo drive	filler drive	evaluation electronics	drive control	flow control	fill control
	M	M	M	M	A	A	LE	S	S	S
belt conveyor	0	0	0	0	1	0	0	1	0	0
filler	0	0	1	0	0	1	0	0	0	0
control valve	0	1	0	0	0	0	0	0	1	1
balance	0	0	0	0	0	0	1	0	0	1
servo drive	1	0	0	0	0	0	0	1	0	0
filler drive	0	1	0	0	0	0	0	0	0	1
evaluation electronics	0	0	0	1	0	0	0	0	0	1
drive control	1	0	0	0	1	0	0	0	0	1
flow control	0	0	1	0	0	0	0	0	0	0
fill control	0	0	1	1	0	1	1	1	0	0

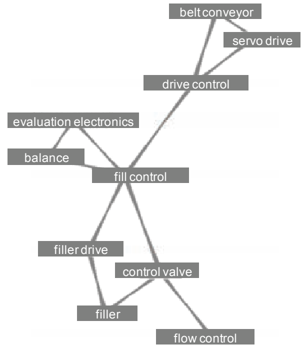


Figure 6. Physical component structure; in form of as $DSM_{C(C)}$ and the associated strength-based graph

3.2 Preparation of the Cost Data

Similar to the product data, the cost data is available in a very different level of detail for the different enterprises. Nevertheless, the following cost information could be assigned nearly consistently to all system components:

- Direct material costs
- Material overhead costs
- Direct manufacturing costs
- Manufacturing overhead costs

Thus it could also be distinguished between pure purchase components and components with own manufacturing portion. In some cases it was additionally possible to further split up the manufacturing costs into costs of individual manufacturing steps. Only the data of enterprise "A" allowed for the explicit reconstruction of the overall integration and appraisal costs.
Besides, the very different and altogether rather limited availability of cost information confirms the knowledge compiled within the scope of other present studies [6, 17].

4 ACCOMPLISHED ANALYSES AND DETERMINED MEASURES

Different structural characteristics and measures (among others, from [16]) were pulled up in the present course of the study for the comparable description of the systems, their components and their cost structure on the basis of the described material. Nevertheless, the following listing will still be extended in the further course of the greater project. So far unconsidered characteristics and measures for the description of the product complexity can be found for example in [18] and [19].

4.1 Analyzed structural models

As already shown on the basis of the simplified filling system example in chapter 3, different structures of the regarded systems were generated. For investigation purposes, these were provided clearly with additional information as shown in figure 7. The recognition of correlations (see chapter 5) could be considerably simplified by this graphic processing of the dependencies.
Altogether the following structures were set up and graphically prepared:

- Design Structure Matrix of the physical component structure $DSM_{C(C)}$
- Strength-based graph of $DSM_{C(C)}$ with additional information about discipline, costs and purchase
- Domain Mapping Matrix of the allocation of components and functions $DMM_{F\text{-}K}$
- $DSM_{C(F)}$ as representation of the functional component structure, calculated by means of equation 1
- Strength-based graph of $DSM_{C(F)}$ with additional information about discipline, costs and purchase

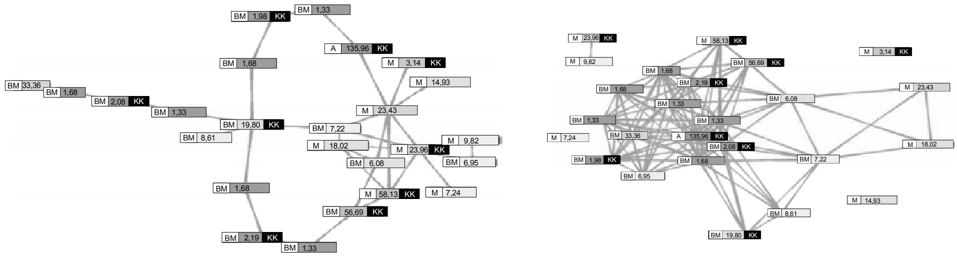


Figure 7. Physical (left) and functional (right) component structure with additional information on discipline, cost and purchase

4.2 Component-specific characteristics and measures

The characteristics and measures can be differentiated in component-specific, system-spanning and function-specific. Below, the component-specific characteristics considered for each component are specified:

- Component-specific cost information: component costs, direct material costs, material overhead costs, direct manifacturing costs, manufacturing overhead costs
- Distinction of complete purchase parts and parts with self-manufacturing portion
- Discipline affiliation
- Number of physical and functional interfaces
- Number of functions assigned
- Affiliation to complete clusters [16] of the physical and functional structure
- Classification into the categories leaf, articulation node, isolated node [16] and/or part of an isolated cluster of the physical and functional component structure if applicable
- Associated manufacturing steps with manufacturing classes, production times and hourly rates (where available)

4.3 System-spanning characteristics and measures

System-spreading characteristics and measures describe the system as a whole. The following were determined:

- System-spreading cost information: total costs, sum of direct material costs, sum of material overhead costs, sum of direct manufacturing costs, sum of manufacturing overhead costs
- Percentage of complete purchase
- Percentage of the involved disciplines regarding component numbers and share of costs
- Percentages of the different kinds of flows connecting the components
- Degree of connectivity (DOC) [16] of the physical and the functional component structure
- Degree of cross-disciplinary connectivity of the physical and the functional component structure
- Number, size and share of costs of all clusters of the functional and the physical component structure
- Percentage of the different manufacturing classes of the production costs (where available)
- System-spreading costs of integration and test (where available)

4.4 Function-specific characteristics and measures

Apart from the component-specific and the system-spanning characteristics and measures, two function-specific characteristics were included in the system analysis:

- Component aggregation: number of components necessary for the fulfillment of the regarded function
- Function costs: Sum of the associated component costs

5 IDENTIFIED CORRELATIONS AND RESULTING FINDINGS

After the analysis described in chapter 4, the recorded characteristics and measures were processed in tabular form and analyzed in their combination. Over the regarded systems numerous meaningful correlations could be identified. Some of these will be introduced in this chapter. Thus the study's significance and the quality of the resulting statements is presented.

5.1 Component-specific findings

At first, the rising cost responsibility of procurement and purchase, as already pointed out by Nißl and her investigations [20], could be confirmed. It shows that regardless of the disciplinal composition, the material costs carry more weight than the production costs. The portion of completely purchased components amounts to on average 38.19%. This results in more interdisciplinary, cross-enterprise cooperation which in turn cause additional development costs [6]. Primarily complicated mechanical components, partly of atypical materials (e.g. special plastics), drives, sensors, special power electronics and components of special disciplines (e.g. optical systems) are bought as complete assemblies. It is particularly remarkable that these completely purchased system components are often very strongly interlinked in the physical component structure.

Strongly interlinked system components (i.e. components with many interfaces) of the physical and also the functional component structure generally show clearly higher costs than the remaining components of the structure (Fig. 8). They are easy to locate in the structures as they tend to arrange in the centre.

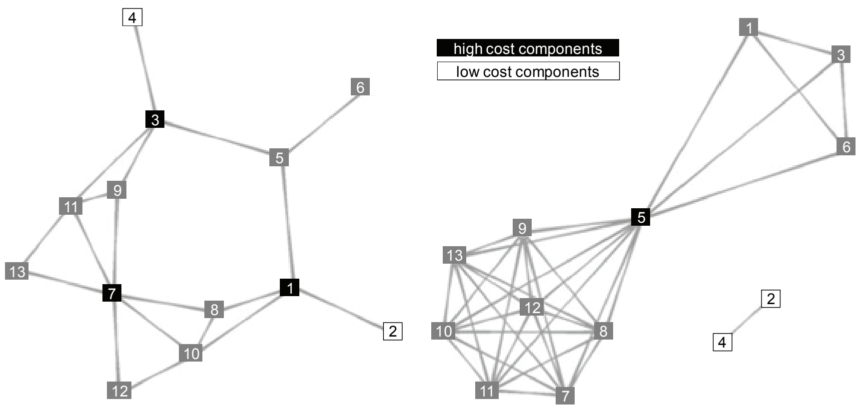


Figure 8. Identification of high and low cost components in the physical (left) and the functional (right) component structure

Exceptions arise, if the regarded "central node" of the physical structure is at the same time an isolated node (and/or part of an isolated cluster) of the functional structure. This finding is also valid for the special form of an Articulation Node. Furthermore the most upscale components of a system are tendentiously members of numerous complete clusters of the physical as well as the functional component structure.

A "leaf-element" of the physical component structure is often an isolated node (or part of an isolated cluster) of the functional component structure and in this case comparatively low-priced. It is to be noted that leaf-elements of the physical component structure are usually interfaces to other assemblies or control units, covers or casings of the overall system.

Further statements specific to the involved disciplines can be derived from the available data:

1. For example it shows that energy and data cables are more expensive the more functions they connect.
2. Small parts of electronics result due to high hourly rates for assembly, connection technique and test in high production costs if being self-manufactured.
3. Mechanical components are usually more expensive than components of other disciplines and
4. Strongly interlinked mechanical components have remarkably high production costs.

5. Motionless mechanics are tendentiously very strongly interlinked so that a high percentage of motionless mechanical parts leads to a high degree of connectivity DOC of the overall system

5.2 System-spanning findings

This category mainly comprises statements related to costs of system-spanning activities such as integration and test. So for example it could be recognized (within one enterprise) that a higher degree of connectivity of the physical component structure leads to comparatively higher costs for integration and test. As a measure for the interdisciplinary connectivity of a system, the degree of cross-disciplinary connectivity (CDC) was introduced (Fig. 9). It appeared that CDC is higher the more disciplines are involved in a system and that an increase of CDC results in higher system-internal appraisal costs.

	belt conveyor	filler	control valve	balance	servo drive	filler drive	evaluation electronics	drive control	flow control	fill control
	M	M	M	M	A	A	LE	S	S	S
belt conveyor	0	0	0	0	1	0	0	1	0	0
filler	0	0	1	0	0	1	0	0	0	0
control valve	0	1	0	0	0	0	0	0	1	1
balance	0	0	0	0	0	0	1	0	0	1
servo drive	1	0	0	0	0	0	0	1	0	0
filler drive	0	1	0	0	0	0	0	0	0	1
evaluation electronics	0	0	0	1	0	0	0	0	0	1
drive control	1	0	0	0	1	0	0	0	0	1
flow control	0	0	1	0	0	0	0	0	0	0
fill control	0	0	1	1	0	1	1	1	0	0

DOC = **12** / 45 = **26,67%**

	belt conveyor	filler	control valve	balance	servo drive	filler drive	evaluation electronics	drive control	flow control	fill control
	M	M	M	M	A	A	LE	S	S	S
belt conveyor	0	0	0	0	1	0	0	1	0	0
filler	0	0	1	0	0	1	0	0	0	0
control valve	0	1	0	0	0	0	0	0	1	1
balance	0	0	0	0	0	0	1	0	0	1
servo drive	1	0	0	0	0	0	0	1	0	0
filler drive	0	1	0	0	0	0	0	0	0	1
evaluation electronics	0	0	0	1	0	0	0	0	0	1
drive control	1	0	0	0	1	0	0	0	0	1
flow control	0	0	1	0	0	0	0	0	0	0
fill control	0	0	1	1	0	1	1	1	0	0

CDC = **10** / **12** = **83,33%**

Figure 9. Comparison of measures: degree of connectivity DOC (left) and cross-disciplinary connectivity (right)

The existence of different kinds of flows (forces, material, signal or energy) within an assembly also has a negative influence on the test costs. The implicit knowledge about this correlation might be one reason for the avoidance of different flows in today's mechatronic products: So for example in an mp3 player many flows are very similar, as they are only information flows on an electrical basis with minimum current and voltage. In contrast to that in a former tape recorder the tape itself presented a flow of matter and additional flows were caused by for example, the mechanical energy flow through the belt to drive the tape, electrical energy flows to drive the different motors and a complicated information flow [4].

5.3 Function-specific findings

A finding in this category is for example that functions whose fulfillment requires many other parts are tendentiously expensive. However the number of fullfilled functions does not directly permit a conclusion about the amount a component will cost: Four categories of components can be formed regarding their percentual affiliation to functions and their share of costs.

- Low costs – low functionality: the bigger part of the analyzed system's components belongs to this category
- Low costs – high functionality: this category is mainly represented by cabling, simple power electronics such as drivers and small moving mechanical parts such as pinions and chains
- High costs – low functionality: this category comprises complex sheeting and housing parts and costumed parts from other disciplines such as optics, magnetic or fluid mechanics
- High costs – high functionality: actuators and control units can be found in this category

6 FUTURE WORK

The results collected so far provide a very promising insight into the cost origin of mechatronic products and the study will still be expanded in the near future. Thus more characteristics and measures will be incorporated in the considerations and at least two more systems will be analyzed. Thereby the parameters will be categorized in order to assure a systematic analysis. On the basis of the already existing findings and follow on research, support for the developer should be achieved by the integration in the “design to cost” guideline introduced in chapter 2. Thereby the intended support encloses, on the one hand, the indication of concrete potentials for cost-reducing concept revisions, and on the other hand the submission of first design rules, that offer situation-specific constructional revision proposals. In a further step, it is desirable to also include development costs in the study as well as in the resulting guideline.

ACKNOWLEDGEMENTS

We gratefully thank the Deutsche Forschungsgemeinschaft (DFG) for supporting the project “Kostenfrüherkennung mechatronischer Produkte mittels Analyse multiplanarer Vernetzungen” which is the origin of the presented work.

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After finishing her studies in Mechatronics in May 2005 Stefanie C. Braun started to work as scientific assistant at the Institute for Product Development of the Technische Universität München. There she is occupied with the presented project on optimized target costing of complex mechatronic products together with other projects that focus on the improvement of multidisciplinary design processes.