Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

REVIEWS

Design for Cost—A Review of Methods, Tools and Research Directions

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Abstract | Whether they know it or not, everything designers do influences cost issues, which can be crucial for success on the market. Providing key support, research in design for cost aims to enable designers to make better decisions to develop cost-efficient and competitive products. This review presents basic findings of cost impact on engineering design as well as major achievements in the field of design for cost. Being the most important source for research in this field is industrial practice, a framework for cost reduction projects is included. Recent research work is reviewed, with regard to origins and influences. In this approach, a generic framework is provided, which identifies drivers for future work in design for cost. This review is of value for both academics and industry.

Design for cost: Design methodology that incorporates all important influence factors for cost efficient design.

Content

The initial sections describe the basics of cost accounting as they are required in design and their application. In the introduction we present an overview of the basic problems that arise when dealing with cost in the early stages of product development. In particular, we look at the influence of the market and recent changes. In the following, the importance of design and development for cost causation will be considered. Then the essential business management basics and the associated concepts will be introduced, along with several cost accounting methods. On this basis, factors that influence costs and potential options for cost reduction will be discussed. After that, methods and approaches for dealing with cost reduction and cost estimation will be presented. Because the most important source for research in this field is industrial practice, a systematic methodology (Section 3.1) and framework for cost reduction projects is included. Then, a review on recent research is presented by structuring the area of design for cost in three major domains, and emphasising some recent and future research directions.

1 Introduction

Developing cost-efficient products involves taking into consideration materials, manufacturing methods, transportation, energy consumption, product quality, number of pieces, design concept and more. The awareness of expenses, cost concepts and calculation procedures are very important for the designer. As a result, the designer can already begin evaluating product concept variations based on the projected costs at an early stage and select one or more cost-efficient concepts that can be examined in more detail later.

While in the past these products were largely mechanical, electronics and information technology for mechatronic systems are becoming increasingly important in design; so more and more designers from these fields have to work together to create a functioning system. In the early design phase, the solution space includes a huge number of possible concepts. Therefore, it becomes difficult to analyse and evaluate the influence of each domain on the product concept.

In the field of mechanical engineering, there is a large choice of estimation methods with respect to material expenses and production costs. The evaluation of potential future financial losses and consequential costs comes on top, once the electrical engineering domain joins the project. Within the scope of information technology, expenses are calculated according to the estimated personnel cost for specification, development, implementation and testing (Zirkler 2010). For mechatronic products, cost estimation procedures are still being researched.

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Services offered in connection with a product usually have to be taken into consideration. In this way companies try to secure existing markets, expand within them, or try to open up new markets.

Naturally, there are companies that only offer services (for example maintenance and repair) targeting products or systems of other suppliers. Product manufacturers may not offer this service yet, or the demand on the market might be so high that several companies can offer these services.

Increasingly, e.g., on the basis of legal guidelines, it is becoming necessary for designers to look not only at the production and overhead costs for a product, but all life cycle costs, including the removal of the product from the market. In design to cost (text book), Michaels & Wood (1989) states this very comprehensively: "design to cost explores the entire range of a project from concept selection through end use. It captures the essentials of planning, designing, and carrying out activities or producing outputs within given financial constraints, and comprehensively provides all the necessary tools, techniques, and data to successfully set and adhere to cost goals. It embodies essential aspects of both 'concurrent engineering' and 'total quality management'. The authors show how the disciplines of value engineering, cost estimating, cost control, and quality design are used to establish realistic and attainable cost goals, and the means to carry out projects without exceeding these established targets". In recent times, even more topics have emerged that need to be considered by the designer. Perry (2002) states: 'design for cost is a name for total cost management of a product for its full life cycle. In addition design for cost (DfC) is the hard face of all design for excellence (DfX) disciplines …'

Therefore, the designer should be aware not only of the close topics like Design for Lean (Mascitelli 2007), but all the DfX disciplines, because cost influence will be determined by every design task in every area. An important basis for design for cost is effective cost estimation like (Sheldon et al. 1991) states: 'Design for cost relies heavily on effective cost estimating, so that the designer can use it for a quick check on cost when (s)he makes a decision.'

Design to cost: Design methodology that incorporates cost as a design parameter.

Bottom-up approach: Cost calculation approach that derives the selling price from the basis of expected manufacturing costs plus a company specific overhead rate.

Concurrent engineering: Design method using overlapping or simultaneous design steps to save time.

Value engineering: Design method where the focus is not only on product cost but also on product value for the customer.

Cost estimating: The process of approximating/forecasting costs from preliminary data of the product or estimation object. For this task, several tools and methods are available to support the designer.

Cost control: Monitoring of expenses during the whole product life cycle.

Design for excellence (DfX): Methodologies to address special design requirements.

Top-down approach: Cost calculation approach where the market price determines the cost targets.

Target costing: In target costing, the currently foreseeable product costs and the established target costs are continuously compared to actual and anticipated performance. The target costs are derived from market analysis.

Life cycle cost (LCC): Costs of the entire product life span, e.g. initial costs, one-time cots, operating costs, maintenance costs and other costs.

1.1 *Market change*

In earlier days, there was rather a seller's market in which a company could dictate the price; however, today companies often find themselves in a buyer's market: The buyer or a competitor dictates the price.

There are exceptions, of course, where the products are new to the market, for which there is yet no competition. Here, manufacturers dictate price, and thus as leaders try to set high prices and skim higher profits.

This approach is risky, especially if it is a product that can be easily copied or designed. Smart companies might quickly establish a competition and underbid the first supplier with substantially lower prices.

The subject areas of imitation products, know-how protection and piracy of products were examined by (Ernicke et al. 2010) and (Labuttis & Meiwald 2010).

With 'bottom-up' approach (Figure 1), price was formerly generated from added up costs (material, manufacturing, management) with an additional overhead margin. Today, this would still be possible for companies with strong market position or with products that have unique selling features, special customer benefits or even enthusiasm-activation features. In the now-more-common contrasting 'top-down' approach from the Japanese target costing, the possible market price to be achieved is to be determined first. Seidenschwarz (1991) describes five ways to derive target costs: the most common is to derive target costs from the prices attainable in the market and profit planning, which is the purest form of target costing. In addition, there is the possibility to derive target cost due to design and production factors in relation to existing skills and abilities (production capacity). A combination of both the above-mentioned methods is also possible; nevertheless, this is critical because the direct market and customer reference as well as the method to derive target costs by benchmarking from competitor products is softened or missing. Based on the calculated price, the profit necessary for the enterprise and overhead (including administrative and development costs) is deducted. The remaining cost target is the manufacturing cost of the product. This value is given to the designers or product manager as the cost target, which he should be able to attain or reduce further with the result of his work, system, product, or component. Depending on the size of the system or product, it can be useful to break down the cost target into partial goals.

1.1.1 Total cost: The total cost comprises manufacturing, administrative and development costs (see Figure 2).

1.1.2 Life cycle cost: The life cycle cost (LCC) consists of the costs incurred at the product

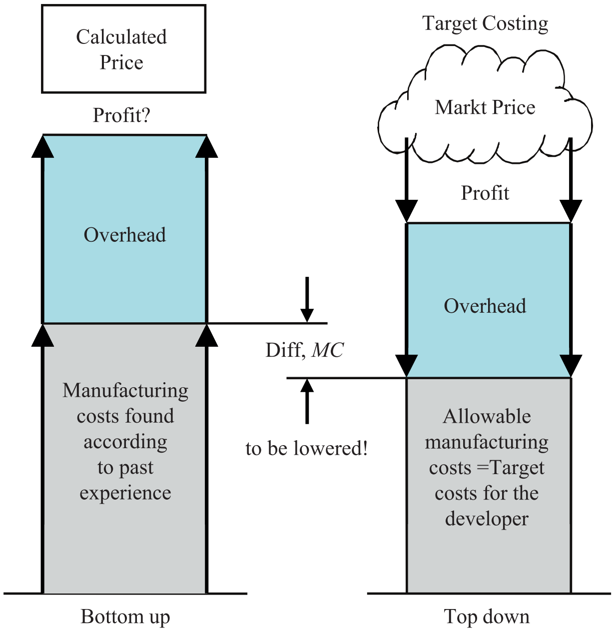

Figure 1: The market price determines the cost target (not the expected manufacturing costs, but the market price!) (Hundal et al. 2007, translated from 5th ed. of Ehrlenspiel et al. 2014).

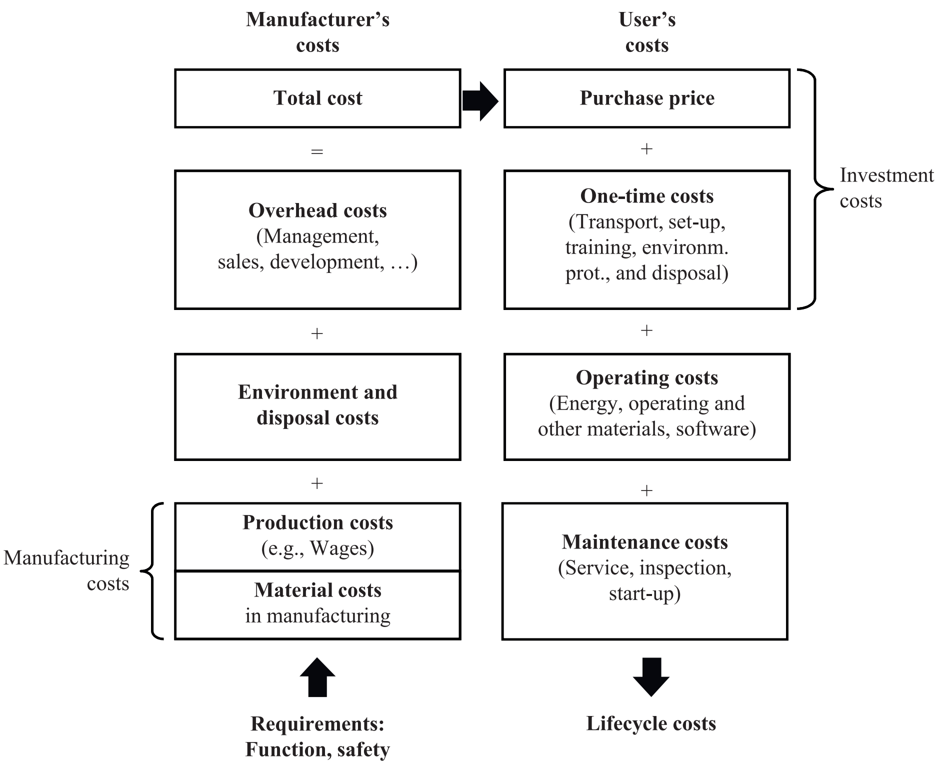

Figure 2: Composition of lifecycle costs (Hundal et al. 2007).

manufacturer (total costs plus profit margin), the profit margin, and all the accumulating costs while the product is used, including its recycling (see Figure 5).

This may include possibly several cycles of product use, if the product is subjected to modernization or upgrading, and therefore, is again- or re-used in identical or similar form (Phleps 1999, Mörtl 2002).

The amount of the shares of the different types of costs (investment-, operating-, maintenance-, disposal costs etc.) can be very different depending on the product: A screwdriver has, for e.g., no operation and maintenance cost. In contrast, a professionally used motor vehicle causes—as a result of the higher miles achievement—more operational and less investment cost than a privately used car, whose cost focus is rather on investment cost.

1.2 *Cost responsibility in the early stages*

The previously referred aspects can already show that it is becoming increasingly important to involve cost analysis and cost considerations as early as possible in product design.

A publication from 2006 (Nißl 2006) outlines that for about 25 years since this publication, no company or industry investigation was published to review, or, if necessary, update any aspects of the distribution of the cost responsibility displayed in the VDI-Guideline 2235 (1987), see Figure 3. This representation of 1987 as well as recent publications, therefore, rely on three sources: (Bronner 1968), (Ehrlenspiel 1980) and (DFG 1978). In international literature, we can find a similar pattern, where some authors mistakenly even go on to state that later phases in product design should also be addressed as having important influence on cost (Barton et al. 2001).

Relative cost figures: Quick tool for calculating product costs with graph support.

Cost estimating relationships (CERs): Mathematical functions that calculate costs of a new product based on one or more parameters to simplify cost estimations.

Therefore, one has to extrapolate not only the cost target that needs to be undercut, but also the cost resulting from development, management and prototyping, i.e. spent cost during the project period that already incurred. It is most important making an early and qualified estimate of the future product costs (material and production costs): how much the product will cost that we are planning and developing now? What assembly effort do we have to expect? What costs until the product or system ready for use by the customer? Because only with early knowledge (estimation) of later incurring costs it would be possible, at the right time, to plan and execute the right measures to reduce product costs.

Evaluation of the prospective cost is based on imperfect information at the early stage. Yet, a variety of possible and proven methods and tools have been developed to solve exactly this problem. These range from quickly applicable relative cost figures or cost estimating relationships (CERs) (e.g. based on product mass/weight) to more sophisticated software systems (E.g. HKB, Facton, XKIS, KosKA, CoCoS, etc.), which require maintenance of their supporting databases (Reischl 2001, Nißl 2005, Gahr 2006, Hellenbrand et al. 2010).

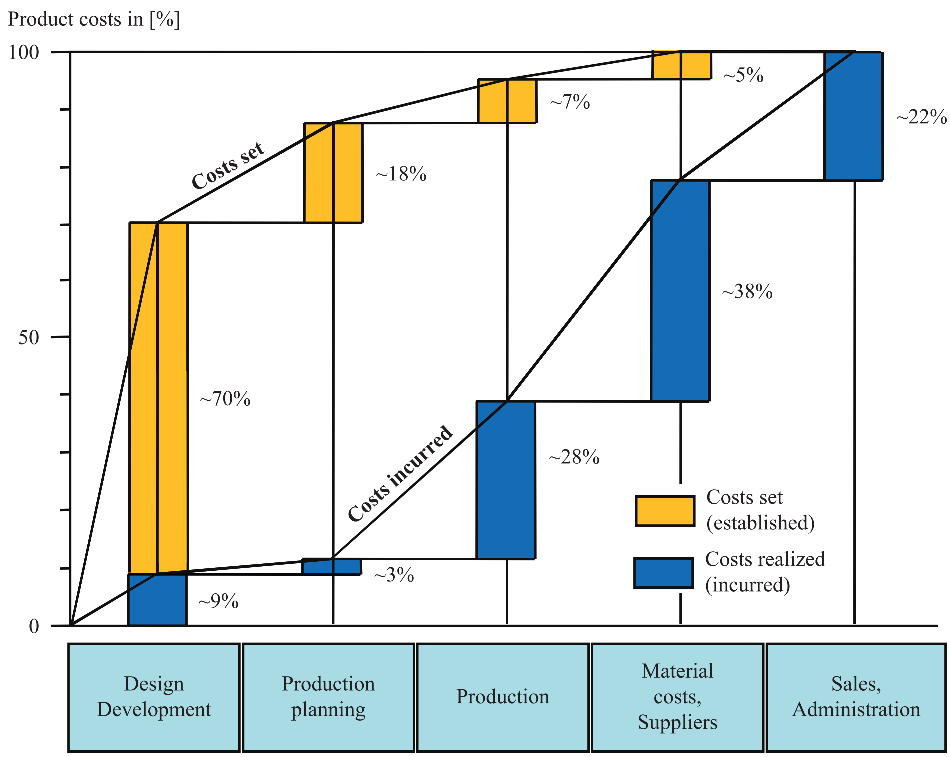

Figure 3: Costs set and costs incurred in different departments (VDI-Guideline 2235 1987).

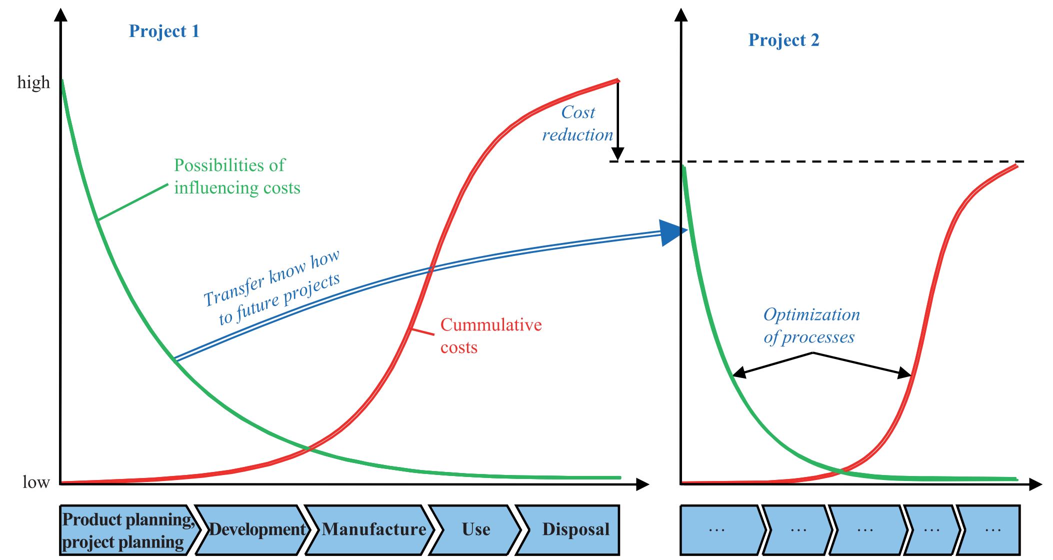

Figure 4: Possibilities of influencing and establishing costs—know how-transfer to future projects (Mörtl 2012). The image has a similar statement as the figure in VDI-Guideline 2235 (1987).

Not all cost information is available when a project starts. This, on the one hand, depends on how precise, up to date, and extensive the basis of current cost information for currently manufactured products, former products and their prefabricated parts and design steps is. On the other hand, cost data in the literature on other companies and products are not transferable 1:1, since this in turn depends on a variety of factors: for example, the specific situation (location, facilities, wage levels, laws etc.), the product (e.g. variants, complexity), or major influencing factors on the costs (material, size, number of pieces, etc.).

It is virtually impossible to make cost estimate hit the bull's-eye for the first time. Cost estimation must be practiced, one has to gain experience and continuously expand the supporting data base.

Cost estimation: Forecasting of costs.

If one completely neglects cost management, the risk of developing too expensive a product and causing a failure in the market will be high. Such situations have often led to bankruptcy of companies. For highly-priced products, cheaper competitors can also more easily emerge.

For companies to survive in the long term, long-term strategic as well as short-term tactical measures need to be employed. Though cost management primarily concerns the strategic area, short-term measures may also be necessary to be implemented. Cost management is targeted control of resources to achieve a profit and competitive advantage in the long term. This includes constantly repeated evaluation of costs, and active continuous improvement using systematic approaches.

Cost management: Targeted and systematic steering of costs.

Above all, the developers involved in the early stages of the product development process themselves consume costs (salaries), and are, on the other hand, responsible for the costs incurred in the later parts of the product life cycle (materials, manufacturing, purchased parts,... maintenance costs, recycling). For meeting the requirements given to them by the management, sales departments, and product managers, designers have a particularly high level of responsibility in adhering to the cost targets for the product to be manufactured. Staying within the target cost can be facilitated and improved if cost information from previous, similar or external products is accessible (Figure 4). A good documentation and search is an important step in this direction.

In the early stages, numerous possibilities are available for the designer to influence the later-incurring costs. In the course of the project progress, these chances drop rapidly. Figure 3 shows that the later the changes in a product design are carried out, the more expensive the products eventually will be.

2 Influences on Cost Reduction

With the basic knowledge of business management and cost accounting from the previous section, we now examine the most important parameters. It has been shown that the early stages of product development have a big influence on the product concept, production costs as well as life cycle costs.

Figure 5 highlights some parameters that influence production cost, broken down into three

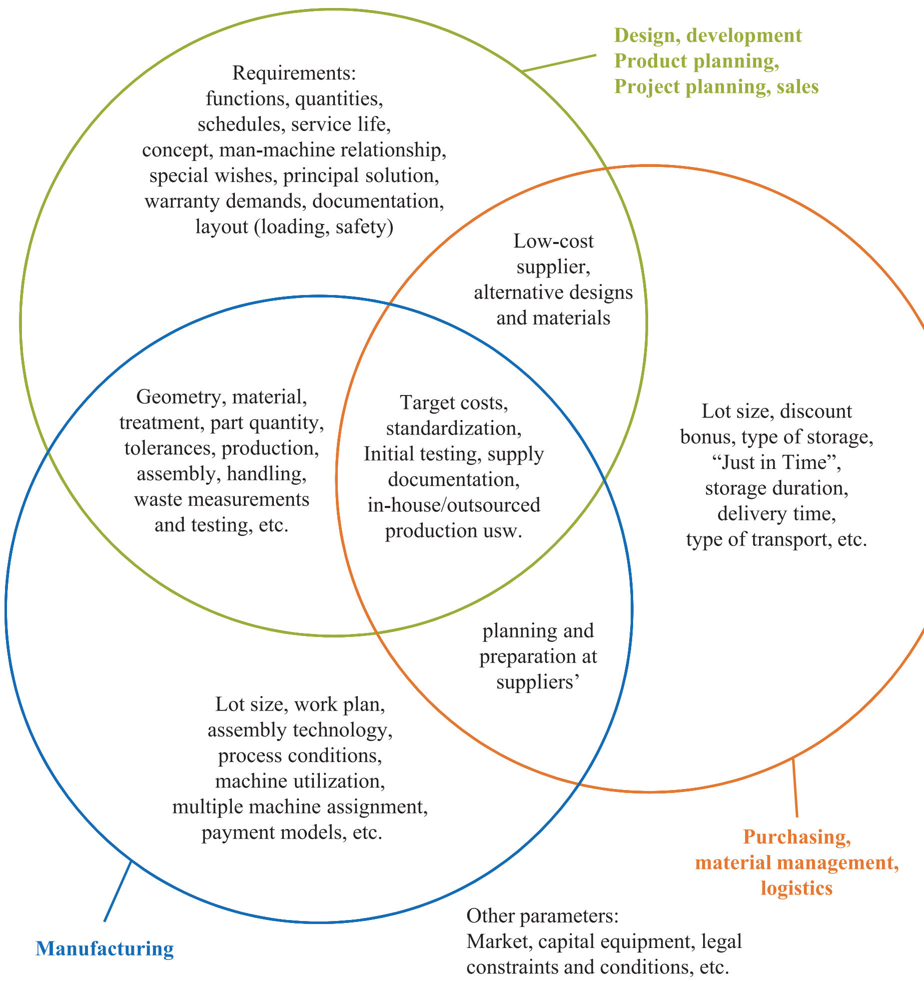

Figure 5: Examples of parameters affecting manufacturing costs (Hundal et al. 2007).

different elements. The elements or departments have special competencies with which they influenceproductioncosts.Inordertoexertinfluence on certain parameters, several departments need to co-operate closely and deal with areas of overlap in responsibility. An optimum must be found within complex interdependencies on total costs. If everybody in the departments is working just on his own, it could be that a minor change, e.g. the cost of materials, given by the purchasing department leads to a substantial increase in the production costs. As a result, the product cost could increase. These errors can be avoided by close cooperation and an open exchange of information.

One must look at the network of influence parameters repeatedly and make decisions with regard to the optimisation of the relationship between, say, manufacturing methods, batch size, number of pieces and capital requirements. As a rule, the higher the number of pieces, the more automated the manufacturing process will be (particularly for high wage countries). The investment in the machinery will also be higher, but batch sizes can be higher as well. However, the demand for a reduction in capital charges (e.g., storage charges) comes along with a reduction of batch sizes (because more frequent delivery to the customer becomes necessary) that subsequently requires more frequent set-up of the machinery. Special demands for the quick set up of the machines are made, which raise the cost of the system again, meaning that the cost for more frequent changes of the set up (= set up cost) have to be covered by lower batch sizes.

In the following, some influence parameters are examined. For additional parameters and the possibilities to influence costs, see Hundal et al. 2007.

2.1 *Requirements*

A clear definition of tasks, requirements and customer requests (see Figure 5) can reduce costs. Accordingly, product developers should be integrated into a project team at this stage to understand the customer needs early, which could result in lower costs.

On the other hand, the requirements have to be re-checked and scrutinized constantly. High expenditure can be caused by too-high requirements, guarantees, acceptance conditions and the fulfilment of legal requirements.

2.2 *Concept*

New product concepts must fulfil new market requirements as well as be substantially cheaper, as illustrated below.

- Electromechanical switches consist of five to six parts, but are suitable for higher current. Membrane switches, in contrast, consist of only three parts (top, inner and bottom membranes), save space, and are lightweight with 50 to 70% cheaper production costs.
- Before the oil crisis in the 1970s, container ships were driven by medium sized diesel engines increasing cargo volume; however, they required higher-quality, more expensive fuel. Due to the rising fuel prices, these engines were replaced by low speed diesel engines, though they needed more space, which reduced the cargo size, they could burn cheap fuel. This new concept led to an overall reduction in life cycle costs (Hundal et al. 2007).

2.3 *Shape*

Shape includes the entirety of the geometric features of a product. These are fixed while sketching and working out. There are guidelines, like for example, 'from the most important to the least important'.

In designing, not the first-best solution should be implemented, but to look for alternatives (Figure 6) and to evaluate them technically and economically.

2.4 *Quantity*

Quantity is a very significant factor influencing production costs. With increased quantity or lot size, fixed costs (e.g. advertising, proposals, manufacturing planning, purchasing and shipping operations, material testing, etc.) are shared by more produced parts. Larger quantities also generate training effects (learning curve) that lead to acceleration of work procedures and reduced costs.

Fixed costs: Fixed costs are those whose value is independent of the appearance of a specific cost-controlling variable. In contrast to variable costs, these are costs whose value is dependent on the appearance of a specific cost-controlling variable (e.g. material direct costs).

If production costs of a component have high setup cost proportion, so the setup costs decreases very quickly when quantities increase, even when quantity is increasing only slightly. If production

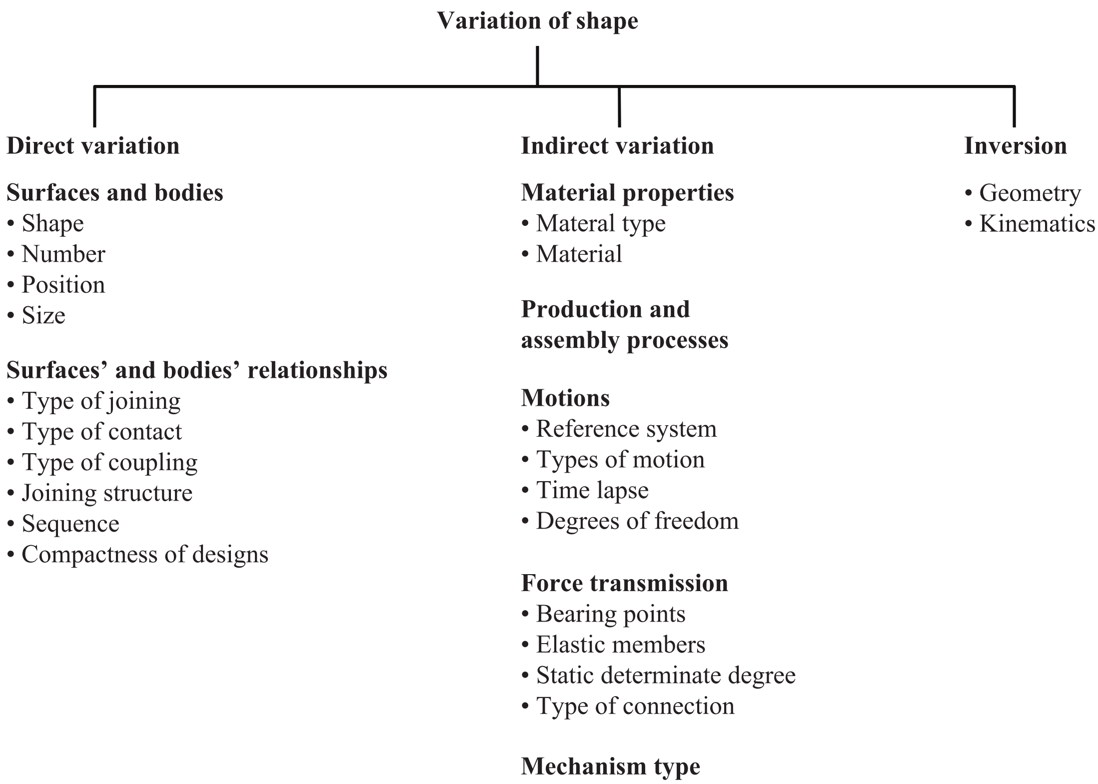

Figure 6: Overview of shape variational features (illustrative sketches and examples are given in (Hundal et al. 2007).

costs have a low setup cost share, the set-up costs per piece decrease only slightly, even if the quantity increases more. This rule to 'increase quantity' is effective for cost reduction, particularly for high set up or fixed costs.

For companies producing low quantities, measures for cost reduction should rather be, say, for reducing material costs, production costs or variants management.

2.5 *Size and dimensions*

For calculating cost changes for size adjustments, the size ratio φ is applied:

$$MC_1 = PCs_0/n * \varphi^{0.5} + PCe_0 * \varphi^2 + MtC_0 * \varphi^3$$

φ = the typical linear dimension of the succeeding design l_1/the typical linear dimension of the basic (initial) design l_0. With index 0: cost of basic design; manufacturing costs MC_1: cost of succeeding design; n = quantity.

For the cost of modified size, the cost shares *MC*, *PCe* and *PCs* influence cost by different proportions. The exponents are applicable for rough order of magnitude assessments, but can still vary in detail:

- The material costs grow with the third power of the size ratio, because the material is a solid: $MtC_1 = MtC_0 * \varphi^3$.
- Production costs from individual times grow with the square of the size ratio, since processing steps are usually dependent on the surfaces: $PCe_1 = PCe_0 * \varphi^2$.
- Production costs from set-up times grow in the ratio $PCs_1 = PCs_0 * \varphi^{0.5}$.

Therefore, it is apparent that by changing the size, primarily cost of materials can change substantially. The changes in production costs from single- and set-up times remain lower in relation to the changes in material costs.

Overhead costs: All costs that cannot be directly assigned to an allocation object or to an application (e.g. salaries of management). Therefore, overheads are also called 'indirect costs'.

The rule derived from that, to pursue small design, yet, must be seen under concurrent attention to the objective. If smaller design e.g. requires changing materials (expensive special materials) or complex lightweight design, this can also result in a more sophisticated manufacturing method with even increased cost!

2.6 *Manufacturing and assembly*

According to VDMA (2006), production costs represent a high percentage of total costs, approximately 28% in mechanical engineering. On the other hand, there are a number of processes for the whole spectrum of primary shaping, deformation, separation, joining, property change and coating processes. Even if only one small number of procedures gained acceptance and became industry standards, some procedures could bring cost savings to even a one time cost (effort) (introduction, training, know-how accumulation) dealing with a new manufacturing method, or mounting procedure may deter many companies from investing in technology and capital. It has to be mentioned that companies with new, innovative manufacturing processes definitely have the chance to take over a cost- and market leadership. When choosing a cost-efficient manufacturing method, attention has to be given not only to the quantity, availability, reliability, delivery time etc.—but also to the interlinking of shape of parts, material, connecting processes and design structure. Note that this could possibly make a further redesign necessary.

2.7 *In-house manufacturing and outsourcing*

In connection with manufacturing, one needs make a choice as to whether to 'make-or-buy', i.e. outsourcing. In this case, there is a variety of pros and cons to be weighed. Arguments in favour of a performance-depth reduction may be, for example, a higher flexibility with order fluctuations and a lower capital commitment. The know-how loss, possible supply outages or insufficient quality, and the increased overhead for coordination with the suppliers are the negatives. If one looks at the decision 'make-or-buy', cost needs to be taken into account, since purchased parts cause additional costs for the company, in addition to the purchase price, like order processes, receiving of goods, material testing, or storage costs. Often, these are accounted for as overhead costs.

2.8 *Variants*

During market analysis, information about possible future variants and their potential quantities can be obtained, also about the estimated time when they would be requested on the market. Even the company's external causes for these variants are diverse: increasing competition, demand for product individualisation, differentiated ergonomic requirements of globally dispersed customers, global different climatic conditions, prevention of product piracy, etc. The reasons within the company may be, for e.g., the lack of cooperation between departments, an unsystematic change management, lack of an effective, rapid system for search of repeat parts and similar designs, the missing use of experience and on an insufficient internal standardisation system. In many cases, the sales department may also raise the variety of variants in design and development, accepting special orders and customized solutions. A task of the variant management in the sense of reducing costs is to increase quantities (e.g. using similar design or repeated parts), thus influencing fixed costs (e.g. drawing practice, item numbers) and to affect variable costs.

3 Cost Estimation and Quick Calculation Procedures

Cost estimation in the early phase of product development is done using cost estimation or quick calculation procedures. Besides computational tools, organizational boundary conditions are also necessary for obtaining a speedy and exact cost estimate. A cost estimate has several objectives, including:

- Continuous calculation and control during the product development process.
- Comparison of actual costs with the previous estimate and with the current cost target.
- Comparison of variants on component or functional level.
- Early detection of cost reduction opportunities.
- Supporting development and sales department for proposal submission.
- Control of supplier offers and compare with own estimates.

3.1 *Methodology*

There is a variety of methods for systematic product design. In part, these can also be adapted and applied in cost reduction projects. First, some fundamental questions concerning the project need should be addressed are:

- one-time cost reduction vs. repeated cost reduction project
- time-criticality
- small vs. large cost reduction
- whether single, small, or mass-produced.

By answering these questions, a project manager can make an initial assessment for possible methods. Though a method should show a certain guideline, no uniform recommendation is possible on account of the very different project types. Therefore, a method is required in most cases which allows a flexible approach to the designer. Only in rare cases where the designer still has little experience with cost-reduction projects, a rigid approach makes sense. Experienced designers will rather employ flexible methodologies, where they can set the focus of their work according to the above mentioned questions.

The procedural cycle of how to reduce cost of products (according to Hundal et al. 2007) is shown in Figure 7 in compressed form. Under item II of the procedure cycle, suggested questions, including notes in part are given in Section 2. Answers to item III are given in the following paragraphs.

Mörtl (2016) recommends preparatory steps that are necessary even before a project officially starts. This guides project managers and team to become aware of targets and project scope, and enables a better planning. Thus, this will facilitate the processing of subsequent, detailed steps within the project.

Not every cost reduction project can be carried out under the same conditions, and with the same methods and tools. Once the time frame for the project available changes, in another case, the design freedoms to achieve cost reductions may alter. Therefore, different cases need to be treated differently. The proposed procedural model is useful for those that need to initiate, guide, or perform new cost reduction projects. Responsibility for a cost reduction project can be in operations (design, development) as well as in overall areas (product manager).

Procedure

The described procedural model follows the principle 'from coarse to detail'. First the coarse, oriented questions about the system to be worked on in the cost reduction project are answered. Then the degrees of freedom within the project framework relating to functions, design, manufacturing processes and others are analysed. After this, the cost structure is examined, and the essential cost impact factors are identified. Detailed analyses be carried out subsequently.

3.1.1 Initial questions: First, the scope of the project should be decided. These questions serve to answer the following:

- How quickly do cost targets need to be implemented and obtained?

Change management: Covers all aspects of planning and execution of engineering changes.

Cost estimate: Cost approximation as result of the cost estimating process. Estimation goes faster than calculation, even it is less accurate, it is sufficiently enough for many cases.

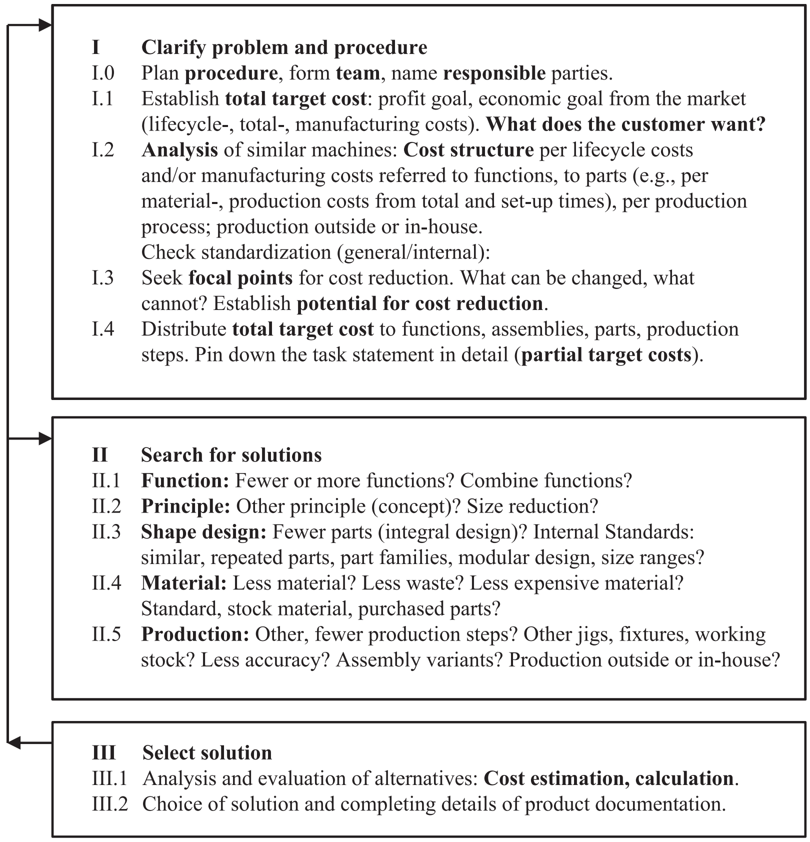

Figure 7: Procedural cycle for cost reduction of products (Hundal et al. 2007).

- Which type of cost target must be achieved: a minor (< 10 percent), a medium (10–20%) or high (over 20 percent) cost reduction?
- Is the project a new design, an adaptation of existing design or a variant design?
- What is the quantity? Is the product manufactured individually, in small or mass production?
- Does the cost reduction project concern the entire product range, one product or only a single component?
- What costs seem relevant in the project: which market is the target? What costs will be major sales argument to our customers? Life cycle, total or production costs?

These questions are not strictly sequentially isolated, nor to be answered individually. They need to be considered in an interconnected manner, because many cost factors and boundary conditions affect each other. If, for example, only one variant is designed and its costs reduced, there might be very little opportunities within a systematic variant management. If the variant is produced in higher quantities, more opportunities in concept, design and manufacturing processes arise for cost reduction.

3.1.2 Analysis of margins: In addition to project boundary conditions (e.g., budget, schedule, staff/capacity etc. as shown in 3.1.1), design freedoms or limitations are also of high importance for a cost reduction project:

- Is the previous task negotiable or can the product requirements be changed?
- Are there margins in the function of the product, or in the feature concept?
- Can alternative product concepts be designed?
- Are there change opportunities in product design?
- Can other manufacturing or assembly methods be applied?

The less the margins in each issue, the less the scope for cost reduction is. This requires thinking in the project not only in requirements and wishes, but explicitly for searching for margins and documenting them.

3.1.3 Preliminary cost analysis: After the early considerations and assessments, it is now necessary to deal with preliminary but more detailed cost issues (if the project is still evaluated as positive and feasible).

Determine the main cost shares of the project: Analyse which costs represent significant shares in the project.

Determine the main cost factors/cost drivers: Examine which parameters primarily influence costs.

Focus on the essential types of costs and identify cost reduction options: Consider how the main costs shares (e.g. costs of material) can be impacted and reduced. Create corresponding ideas (e.g. cheaper procurement, alternative materials, use of prefabricated products or increasing the quantity of purchase).

Select an approach and supporting methods: According to the time available, project scope, necessary cost savings, identified costs drivers or quantities, it may be necessary to select different approaches for the project. There are very different, even industry-specific procedure models, e.g. TOTE scheme, procedure cycle, the munich procedure model (MVM), target costing, integrated value engineering (IVE), value analysis, variant management, etc. (Lindemann 2009). If a method is already established, it is to be examined as to whether it is expedient for the present project. Steps that can be performed in advance even before a big cost reduction project starts now follow.

3.1.4 Detailed cost analysis: Depending on the scope of the cost-reduction project and the project boundaries shown in Section 2.2 (e.g. time, cost target among others), more or less detailed procedure models, methods and tools (e.g. value analysis, VDI standard, ...) must be applied. Mörtl (2016) recommends an advance set up of a transparent cost structure and to start with a simple ABC analysis. This would help recognise the cost focus and gain more knowledge, as described in the beginning of Section 2.3.

3.1.5 Implementation: Procedure models need a detailed plan for cost reduction projects, but requires taking into account staff capacity, budget, dates, safeguard measures, supervisory bodies, organization a consistent cost management, project cost documentation, etc. These organizational steps should be prepared in detail and agreed with the involved departments and individuals.

3.1.6 Concluding remarks on the procedure model: To conclude, it is essential to conduct a costing of the project or product. It should be compared with the previous cost estimate, which will show up as the difference between the earlier estimate and the final costing. This knowledge can be of benefit to future projects in cost estimation corrections, and in adjusting or reducing errors and increasing accuracy.

3.2 *Continuous cost tracking*

In addition to the systematic approach, it is equally important to document the steps and also the changes of costs of a project. It is not enough to determine the cost target only at the beginning of a project. Internal (e.g. company specifications) or external (market) influences move cost objective conditions, and these changes should be tracked in the documentation. Costs planned during the product development process and actual costs consumed (Figure 3) must both be constantly reviewed and costs planned continuously corrected.

A continuous monitoring of costs from project start to the final costing is the key to stay constantly up to date, not to lose the overview about the costs and also to learn from former projects. Even if this task ties up resources, it is essential for a steady know-how growth in terms of cost-effective design and a durable development of the company with competitive products.

A cost tracking table (spreadsheet) is shown in Figure 8. It represents a possible template to anchor the cost topic extensively in a design project, to document, to make for all involved transparent and to constantly monitor (download at http://files.hanser.de/hanser/docs/20130801_2138113324-38_978-3-446-43000-6_Zusatzmaterial.zip). It should be applied at the outset with consistent layout and a consistent cost structure.

The following content can be documented in such a table: Actual costs of the previous product (if any) with its components, component costs and drawing numbers and drawing state, costs of a competitor's product, target costs, and parts of target costs for the new product with component costs.

For these targets, proposals for measures can be established, with clear responsibilities as well as with corresponding milestones and deadlines. In the following meetings, the state of actual cost or the cost estimation of the new parts can then be recorded and compared to predetermined targets.

The targets are controlled, if necessary adapted, and new measures are decided upon. Over multiple

TOTE scheme: Basic Test-Operate-Test-Exit cycle for design decisions.

Procedure cycle: A basic scheme for problem solving, including the steps: task clarification, solution search and solution choice.

Munich procedure model (MVM): A structured procedure cycle that supports the designer systematically from target planning to target attainment in engineering design processes.

Integrated value engineering (IVE): Cost analysis method that combines target costing and value engineering.

Value analysis: Synonym used term for value engineering.

Cost tracking table: Tool to collect all incurred costs to estimate future costs and to compare them with the target costs.

ABC analysis: Method to divide subjects/items into three categories: A = very important, B = medium important and C = marginally important. This helps to focus on most important issues.

Project title: Windshield wiper
Project No.: 2386-US-DC-68
Project manager: EK-49/Kaltenegger

Session 1
01.10.2005

Assemblies / parts	Parts-number	Date of drawing	Number of parts	Actual costs/ part	Sum actual costs	Share	Actual costs competitor	Target: Number of parts	Partial target costs/ piece	Partial target costs	Required cost reduction	Required cost reduction	Cost reduction potential	Responsible	Deadline
Actual							Competitor	Target							
		Date	Pieces	[€]	[€]	[%]	[€]	Pieces	[€]	[€]	[%]	[€]	Measures		Date
Electric motor	28–4659–48	23.4.03	2	6,20	12,40	31,1	9,80	2	4,90	9,80	–21,0	–2,60	Other principle	Development	15.12.05
Drive bar	83–7561–97	22.6.03	1	2,20	2,20	5,5	2,30	0	1,80	0,00	–100,0	–2,20	Other concept: leave parts	Develop. + production	1.2.06
Bearing	93–7583–98	12.8.02	4	1,20	4,80	12,1	5,00	2	1,00	2,00	–58,3	–2,80	Simplify	Development	20.10.05
Whiper arms	83–7562–23	25.6.03	2	4,80	9,60	24,1	7,60	2	6,30	12,60	31,3	3,00	Other concept	Development	20.10.05
Wiper lip	74–5196–74	1.7.03	2	2,80	5,60	14,1	4,40	0	0,00	0,00	–100,0	–5,60	Other concept: Combine with whiper arms	Development	20.10.05
Spray nozzles	38–5628–57	16.9.02	2	0,50	1,00	2,5	0,60	2	0,28	0,56	–44,0	–0,44	Different supplier	Purchasing	20.10.05
Sealing	74–3245–28	1.5.02	2	0,08	0,16	0,4	0,20	2	0,08	0,16	0,0	0,00	Depate prices	Purchasing	20.10.05
Rivets	67–5940–18	20.8.99	6	0,05	0,30	0,8	0,00	4	0,03	0,12	–60,0	–0,18	Depate prices	Purchasing	20.10.05
Several small parts	div.	12.5.03	3	1,25	3,75	9,4	2,00	2	1,00	2,00	–46,7	–1,75	Depate prices	Purchasing	20.10.05
Sum				19,08	39,81	100,0	31,90			**27,24**	–31,6	–12,57			

Project title: Windshield wiper
Project No.: 2386-US-DC-68
Project manager: EK-49/Kaltenegger

Session 2
01.11.2005

Assemblies / parts	Parts-number	Date of drawing	Actual costs	Achieved cost reduction	Target: Number of parts	Partial target costs/piece	Partial target costs	Required cost reduction	Required cost reduction	Measures	Responsible	Deadline
Actual					Target							
		Date	[€]	[%]	Pieces	[€]	[€]	[%]	[€]			Date
Electric motor	28–4659–68	29.10.05	14,50	16,94	2	4,90	9,80	–32,4	–4,70	Other supplier	Purchasing	15.1.06
Drive bar	83–7561–99	29.10.05	2,40	9,09	0	1,80	0,00	–100,0	–2,40	Change production	Production	1.2.06
Bearing	93–7583–05	29.10.05	2,76	–42,50	2	1,00	2,00	–27,5	–0,76	Other supplier	Purchasing	15.11.05
Whiper arms	83–7562–26	28.10.05	7,22	–24,79	2	6,30	12,60			Change concept	Development	15.1.06
Wiper lip	74–5196–75	1.7.03	4,20	–25,00	0	0,00	0,00	–100,0	–4,20	Change concept		15.1.06
Spray nozzles	38–5628–59	16.9.02	0,47	–53,00	2	0,28	0,56			ok		
Sealing	74–3245–29	1.5.02	0,15	–6,25	2	0,08	0,16					
Rivets	67–5940–22	20.8.99	0,29	–3,33	4	0,03	0,12	–58,6	–0,17			
Several small parts	div.	12.5.03	1,22	–67,47	2	1,00	2,00			ok		
Sum			**33,21**	–16,6			**27,24**	–18,0	–5,97			

Project title: Windshield wiper
Project No.: 2386-US-DC-68
Project manager: EK-49/Kaltenegger

Summary
03.05.2006

Assemblies / parts	Parts-number	Date of drawing	Actual costs	Achieved cost reduction
Actual				
		Date	[€]	[%]
Electric motor	28–4659–48	29.10.05	11,78	–5,00
Drive bar	83–7561–97	29.10.05	2,22	0,91
Bearing	93–7582–98	29.10.05	2,00	–58,33
Whiper arms	83–7562–23	28.10.05	6,83	–28,85
Wiper lip	74–5196–74	1.7.03	0,00	–100,00
Spray nozzles	38–5628–57	16.9.02	0,48	–52,00
Sealing	74–3245–28	1.5.02	0,15	–6,25
Rivets	67–5940–18	20.8.99	0,29	–3,33
Several small parts	div.	12.5.03	1,22	–67,47
Sum			**24,97**	–37,3

Project title: Windshield wiper
Project No.: 2386-US-DC-68
Project manager: EK-49/Kaltenegger

Summary

	Session 1 Actual costs old product	Session 2	Session 3	Session 4	Session 5	Session 6	Summary [€]	Summary [%]
	1.10.05	1.11.05	1.2.06	5.3.06	28.3.06	10.4.06	3.5.06	3.5.06
Electric motor	12,40	14,50	14,45	14,45	14,40	12,22	11,78	–5,00
Drive bar	2,20	2,40	2,32	2,28	2,24	2,20	2,22	0,91
Bearing	4,80	2,76	2,52	2,45	2,30	1,98	2,00	–58,33
Whiper arms	9,60	7,22	5,20	7,45	7,32	7,02	6,83	–28,85
Wiper lip	5,60	4,20	0,30	0,00	0,00	0,00	0,00	–100,00
Spray nozzles	1,00	0,47	0,47	0,47	0,47	0,47	0,48	–52,00
Sealing	0,16	0,15	0,15	0,15	0,15	0,15	0,15	–6,25
Rivets	0,30	0,29	0,29	0,29	0,29	0,29	0,29	–3,33
Several small parts	3,75	1,22	1,21	1,21	1,23	1,22	1,22	–67,47
Sum	39,81	33,21	26,91	28,75	28,40	25,55	24,97	–37,3
Target for each session		27,24	27,24	26,34	26,34	26,34	26,34	
Competitor	31,90	31,90	31,90	31,90	31,90	31,90	31,90	

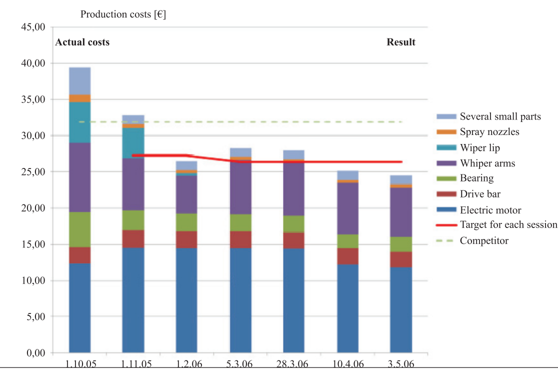

Figure 8: Cost tracking table, virtual, not complete example (Mörtl 2012).

meetings, the cost estimates and calculations are continuously documented until the result is achieved. A graphic can visualise the comparison of actual costs, targets and competitor's costs. Though the final costing of a project on actual costs basis is an unbeloved assignment, nevertheless, it shows a necessary learning effect for future project treatments.

3.3 *Framework for cost reduction projects*

A framework for cost reduction should be applied during or in addition to the daily work of the developer's 'by the way' costs reduction and cost estimation activities. It is a must for larger projects, but can involve high effort. When developing a system, the designer can be quite busy full time, so to collect cost data and maintain the documentation for a continuous and timely cost tracking can be difficult as an additional task for the designer. A cost reduction or value analysis project should, therefore, be initiated by a higher supervisor, a department manager or the executive board. It must be 'installed' and integrated in the company's organization and processes.

Cost reduction teams consist ideally of various departments (design, manufacturing preparation, production, assembly, quality inspection, service, sales, marketing), to be able to implement, evaluate and adjust measures (Arnaout 2001). The employees who work only part-time in the project must be given time for this (agreement between project manager and head of department!). A retraction in the day-to-day business is important to avoid in order not to jeopardize the ongoing project due to reduced resources or delay.

Suppliers should be involved early in the development process in target costing, so as to ensure a trusting and open cooperation (Arnaout 2001). This common goal is to show a growth of the market through significantly reduced costs. In cooperation with the supplier, possible cost savings must be planned, identified, and implemented; this can be achieved inter alia through visits to production lines, disclosure of work plans and calculations of parts as well as by the analysis of error-records.

Methodological approaches in projects and in the daily work of the product designers are to be supported by supervisors. Any necessary method training must be encouraged by the personnel departments.

Managers should not only demand, but also give support and space for the project. Depending on the scope and tension of a cost reduction project, necessarily design freedoms are to be shown to the team. The known killer arguments ('we have tried for ever', 'this never worked') should be prevented. Instead, all opportunities for cost reductions are to be documented and worked through step by step to evaluate costs.

Changes in design that lead to cost reduction should be discussed and evaluated objectively, even together with the customer. Reducing costs not only means having to change, but also being allowed to change—with supportive backing by the supervisors and management.

While reduced costs are quickly apparent in initial cost estimates, the implemented projects are reflected in balance sheets but only in a few months. Measures for costs reduction can be quickly planned and launched, yet their impact will show only later. The contractor of the project must be aware of this, if he has to demonstrate project success with figures.

3.4 *Accuracy of cost estimation*

The earlier cost estimation is performed during the product development process, the less accurate it is; this is because cost estimation is not yet calculated using actual costs. Here accuracy is compromised for speed.

Divergences between cost estimates and the later actual costs can be reduced with the following measures:

- Components that have a higher proportion of costs (A-parts such as e.g. cast housings) of the total product should be estimated more precisely in their costs. In addition, components with a lower proportion of the costs (C-parts such as screws) should be estimated more coarsely.
- A cost estimate is more accurate, if a high number of repeat or similar parts can be used instead of many, difficult to estimate, new parts. For such parts, the costs are usually already known. At the same time, overhead in the drawing or standardization department is reduced, if existing parts are used instead of creating new ones.
- Dividing estimation: One should estimate the cost of a product not as a whole. The product instead should be broken down into sections. This can be done not only for components and processes, but also for features.
- Several people should carry out their estimations independently. The results are averaged, and then outliers are discussed and adjusted if necessary.

On a higher part, mathematical means outweigh random errors at a cost estimate. However, fundamentally, systematic errors such as fear surcharges or risk additions distort cost estimates. These deviations must be balanced out.

3.5 *Reducing cost estimation effort*

Cost estimation as a design-concurrent calculation, by means of quick calculation procedures, may require a higher effort depending on product size, degree of new- or standard parts, and complexity. The work can be simplified, taking into account the following principles:

Cost approximation methods: Estimation method with formulas which use cost drivers and information about similar products.

- Use of purchased parts and norm-parts: Prices are available relatively quickly out of catalogues or from the supplier.
- Use of repeated parts and similar-parts: Costs are already known.
- Use of similar parts: Cost can be determined with similarity laws, e.g. a cost growth law production. This may concern own, known products, or prefabricated parts from other suppliers that can be analysed, for example, by the means of benchmarking.
- New parts: Use them economically, make new calculations, or estimate in a qualified way.
- Simple parts (C-parts): Count and multiply by price.
- Consultancy for production use: a manufacturing specialist should advise developers on the designed parts. This would reduce the change effort and the turnaround in R&D.
- Effort reduction at the increase of accuracy: The cost estimates result are improved as more experience is gathered and practice repeated over several own projects.

Cost growth law: A cost growth law (also called similarity law) is the relationship of the costs of products similar to each other. For that, geometrical, material, shape, and production similarities must exist, which is usually the case for systems in size ranges.

Search- or similarity calculation: A relatively simple and rapid means for determining the costs of new products by using search and adoption of the costs of similar products.

3.6 *Methods for cost estimation*

There is a vast number of quick calculation procedures that can be carried out by hand or assisted/supported by computer. Some of these are simple formulas or software tools that can be purchased. Apart from the cost estimation approach outlined in Section 3.4, some easily adaptable quick calculation procedures will be explained in the following (Sirel 2015), where he proposes a classification/explanation on basis of comparison of method classifications in German-speaking and international literature:

Analytical methods have many synonyms that can be seen in various literature sources. ‘Causal processes’ is applied also as a synonym for this term; ‘causal’ means that there is always a causality in these methods with which the amount of cost can be derived. Planned cost calculation and detailed costing are also considered analytical methods in some literature.

Synthetic methods are based on mathematical and statistical procedures, and require specification of quantity, and availability of detailed design drawings and technical details. Costs are calculated with the help of one or more cost determining factors on the basis of similarity to already manufactured products.

These methods are also known as cost approximation methods or cost forecasting techniques (Schlink 2012). Most international literature refer them as parametric methods (Niazi et al. 2006).

Intuitive methods are described only in international sources, and are assigned to the category of qualitative methods. These are based on the application of previous experience. German research literature does not subdivide qualitative methods further; therefore, this term cannot be found there.

Analogical methods (analogical techniques or analogy-based methods) are based on the comparison of the costs of similar products. *These are called also search- or similarity calculation*.

Cased based reasoning represents a method that takes advantage of the experience from completed projects so as to establish a meaningful estimate of the cost through the use of similarity relations.

Decision supporting methods (decision support techniques) help to evaluate different design opportunities. The main objective of these is to support the cost estimator with stored expert knowledge, so that the estimator can make better decisions at every stage of the estimation process.

Fuzzy logic is a theory that was developed for the modeling of uncertainty. For this reason, fuzzy logic is considered suitable in early design stages where information is still sparse, and of lower accuracy, for cost estimation. Because this method requires a methodically oriented process flow, fuzzy logic takes more effort to apply.

Expert systems are also applied for cost estimation. These are computer systems that use knowledge and inference methods to represent extensive human expert knowledge for solving problems. However, they require high one-time effort to build.

Heuristic rules (rule-based systems) provide, usually, cross-industry guidance on factors or especially costly parts and production methods. The objective of these rules is to support the designer to select the cheapest design alternative while adhering to the quality objectives.

Neural networks determine desired output data with a given number of input data. Several authors have tested this procedure for cost estimation, with promising results.

Regression analysis is a method for cost modelling that is used very often in practice. Using regression analysis, it is possible to find correlations between the explanatory variables and the parameter of interest. The explanatory variables are the characteristics of the product to be identified. The parameter of interest represents the costs or at least a size which can be assessed with a corresponding price factor.

Design equations are a combination of different cost growth laws in a cost estimating relationship. The VDI-Guideline 2225-4 (1997) describes in detail the method of design equations with examples of its application.

Activity based costing represents no new cost accounting system that would be comparable to the traditionally distinct systems of total cost accounting, or the various forms of marginal costing.

The core ideas of activity-based costing can be realised in all these cost accounting systems, but their application focus have so far been confined within total costing. It is also known as process costing. The terms 'activity-based costing' or 'Cost Driver Accounting' are used in English. Gahr (2006) developed a resource-based activity-based costing method, which is referred to as path cost accounting.

Hybrid methods are those that combine several methods in order to achieve better accuracy or to be able to calculate total costs or several cost categories by using the combination.

Computer-aided calculation is based on the use of software to reduce the effort of the preliminary cost estimate, or to master complexity through the use of the software.

For underlying literature on this classification, refer to Sirel (2015).

The review on product cost estimation from Niazi et al. (2006) is one of the most comprehensive papers in the field of cost estimation and still remains relevant.

As introduced above, a variety of quick calculation methods have been developed for cost estimating. These procedures use the knowledge of essential impact factors, known as cost drivers. Example, cost drivers have weight, material or geometric similarity. To be able to apply these methods, data of cost and design properties from former products are necessary. Based on the data of known products/parts, it is now possible, with these formulas and the data of the new product/parts, to forecast new costs. Simple calculation methods are indeed faster to create, but usually are of limited scope and lower estimation accuracy. For their application, boundary conditions need to be considered as well. More extensive methods provide higher accuracy but also require bigger data base, which increases effort to create and apply them. Also, more data/properties must be known about the new part/product.

4 Review of Recent Directions in Research

For structuring the influences that interact in the area of design for cost, we need to consider three important aspects:

- **Cost types** (e.g. manufacturing cost, total cost and life cycle cost)
- **Design-related** (e.g. mechanical design, electrical design, software design and also design methods)
- **Cost analysis** (e.g. cost estimation methods, cost information systems, cost reduction tables, among others)

Cost research in engineering design is not driven by areas that have been researched in the field 'design for cost', but is mainly driven by new demands and possibilities. New demands can arise in the area of **design**. If new manufacturing methods, new technology, new materials or new design methods are developed, unfamiliar and altered cost structures (e.g. proportions of material cost, manufacturing cost, total- or life cycle costs) with altered impact measures for cost reduction will result. Thus, research on specific cost behaviours for the new situations would be required. The same applies to **cost analysis** tools and methods. If new possibilities arise, e.g. from new/advanced mathematical modelling techniques, to increase the accuracy of cost estimates, as well as simplifications of methods for faster and better understanding of design-cost behaviour, new research must be carried out to examine their impact. Successful research should bring benefits, especially in the area of cost analysis methodologies, with faster and more efficient access to cost reduction opportunities for designers.

Design for cost operates in several research areas. Aerospace is one of the largest areas. The most recent review in this field is by Trivailo et al. 2012, which focusses on cost estimation of hardware. Another review addresses cost modelling (Curran et al. 2004), while some basic

Activity based costing: Accounting method that allocates costs to activities and their corresponding resources in the company. Compared to traditional costing methods, it is capable of better factoring overhead/indirect costs (e.g. administrative, supporting and controlling activities) of a product.

Marginal costing: Costing method that is used if we apply direct costing with regard to earnings to the profit or loss account. The margin is the difference between the earnings and the variable costs.

Path cost accounting: Cost accounting method where the individual path the product or alternative design solution goes in company is the basis for cost accounting.

Cost drivers: Main influence increasing costs.

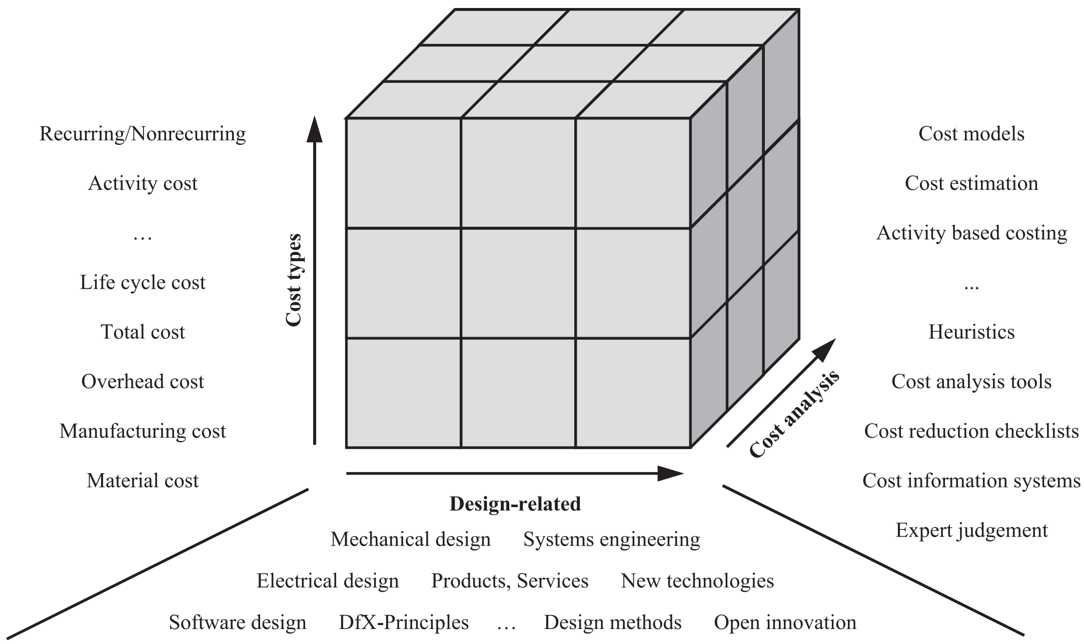

Figure 9: Design for cost sphere.

approaches of cost engineering are introduced by Greves & Joumier 2003. Software development is also quite important for design, and is addressed in the review articles of (Keung 2009) and (Jorgensen & Shepperd 2007). Design for cost was also reviewed by Sheldon et al. 1991.

Other issues in the area of design for cost are addressed by Asiedu & Gu 1998 for life cycle costs, Christensen et al. 1992 for research on estimate at completion, and Roda & Garetti 2014 examine total cost of ownership. The topic 'cost of quality' is examined by Schiffauerova & Thomson 2006 and Lavdas 2008.

Estimate at completion: Forecast of costs to complete a project. Basis for deciding to cancel or proceed with a project.

To show how research on design for cost has generally evolved, we can look at the example of carbon fibre reinforced plastic manufacturing technologies. When the technology appeared and studies come out on its development, the need to analyse changes in existing design for cost strategies arose (Zaloom & Miller 1982). Once a technology gets established, research can be undertaken on cost drivers (Noton 1989). On this basis, guidelines and measures for designers can be derived to better target cost reductions (Gutowski 1997, Kaufmann 2008).

Parametric models: A fast method for cost modelling. On basis of historical product/program cost data, cost drivers are identified that are used in equations and algorithms for cost prediction when little information exists, e.g. in early design phase.

4.1 *Development of cost management—a history*

Evidence of cost management activities can be traced back to the 1880s (Fleischman & Parker 1991), where the activities of British entrepreneurs were examined. Research activities since then can be found in nearly every decade and every industrial sector, e.g. Burton (1900), Seidel (1914), Kresta & Käch (1928), Freund (1932), Ramsler (1948), Kruse (1954), Peat (1968), Rondeau (1975) and more. The most recent textbook on methods and tools for cost estimation is Mislick & Nussbaum (2015).

Cost planning and cost estimation in the aviation and aerospace industries began in the 1930s with parametric models. As computers became more powerful, it was possible to perform faster calculations. Commercial tools developed in the 70s and 80s were also used in other industrial sectors (see Figure 10). With greater amounts of data available and more powerful computers, cost forecasts increased in precision.

In parallel to the computing models and tools, more and more publications emerged. Expanding on the work of Mörtl (2013), we have now collected over 1400 publications of more than 100,000 pages. A detailed analysis of these publications in terms of procedures and tools, phase of application, industrial sector, accuracy and more is part of the ongoing research. The number of studies between 1914 and 1970, as well as from later periods, may be unrepresentative because they have not yet been unearthed. However, we can see a steady development through the 1980s, with a peak at the end of the 1990s; after a quiet period in the early 2000s, the number of publications began to slowly increase. In short, the demand for cost research shows no sign of declining (see Figure 11).

The distribution to industrial sectors of collected literature can be seen in Figure 12, where mechanical engineering represents the main emphasis.

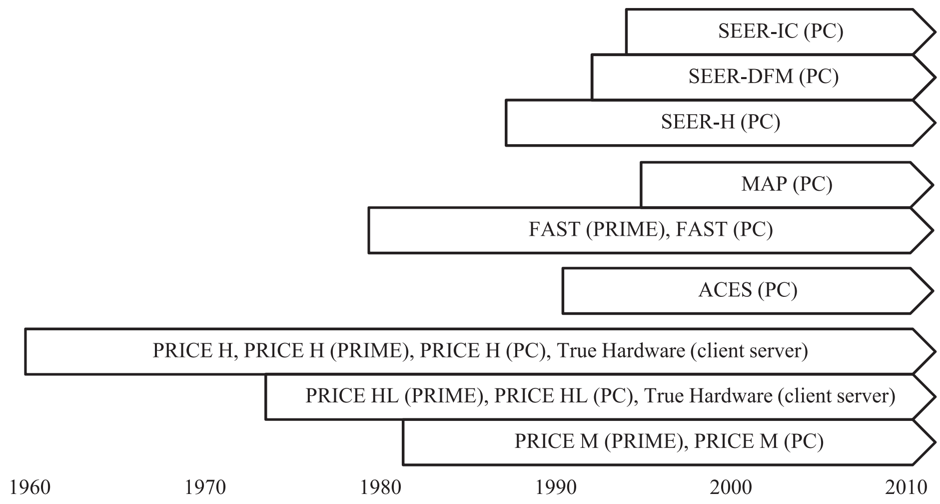

Figure 10: Commercial hardware parametric models (Shermon 2009).

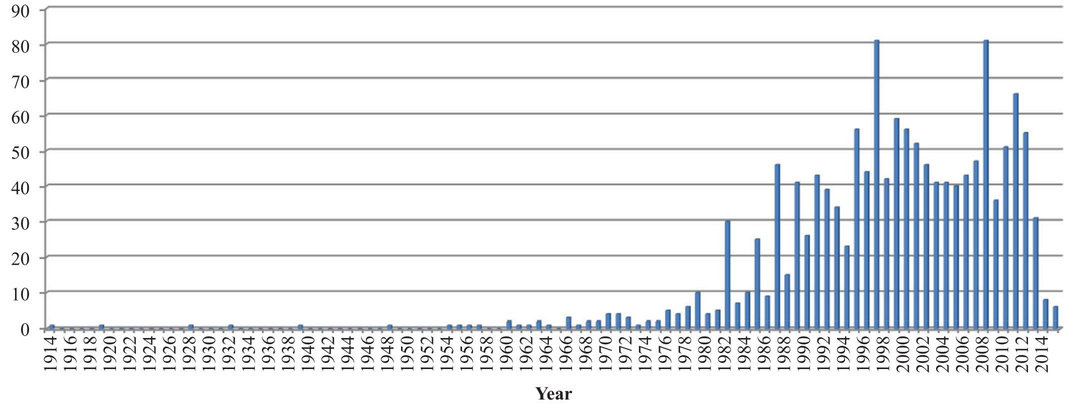

Figure 11: Chronological history of publications on the subject of cost engineering.

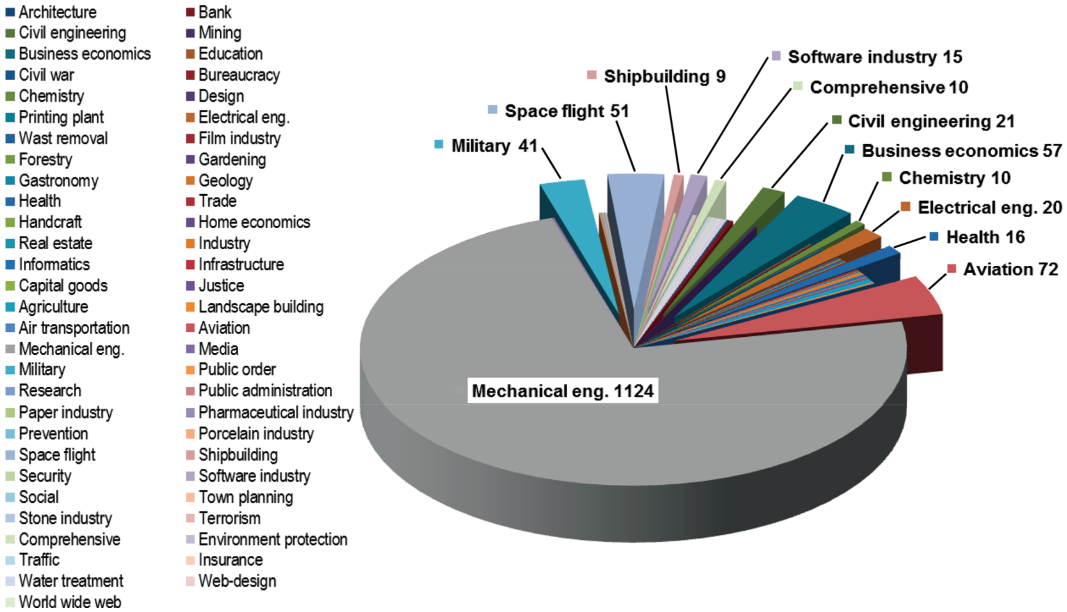

Figure 12: Proportion of different disciplines to publications on the subject of cost engineering.

Feature oriented costing: Costing method where cost elements of concern represents (design) features of the product rather than parts of the product.

Cost accounting: Cost accounting determines where costs originate.

Cost effects: Outcome of costs.

Modularisation: Engineering technique to split products into more independent modules to reduce complexity.

Cost modelling: Using mathematical relations to describe cost behaviour.

4.2 *Cost research since Niazi et al. 2006*

Niazi et al. (2006) classify cost estimation methods and divide them. In the first-level, distinction is made between qualitative and quantitative methods, in addition to intuitive, analogical, parametric, and analytical procedures, see Figure 13.

The advantages and disadvantages of individual procedures are briefly described in Figure 14. Disadvantages considered include time, complexity and lack of information (from previous products, cost drivers, etc.).

4.3 *Recent research*

Recent research has focussed on reducing the complexity of cost estimation and cost accounting practices. Complexity, for example, has arisen due to an apparently unmanageable amount of data, greater product variety because of mechatronic products or product-service systems. If a large amount of data is available, advanced methods like big data tools are employed to make this cost data more transparent.

There are also new features that affect the calculation of life cycle costs: new products, new materials (Das 2011), product-service systems, as well as cradle-to-grave considerations require new approaches to cost estimation (Dhillon 2010).

Foussier (2006a, 2006b) explores the field of statistical cost modelling techniques. Boothroyd et al. (2011) intensely examine the DfX category 'design for manufacture and assembly' (DFMA) in detail with a major cost estimation emphasis.

Cost estimation tools for specific areas have been developed to support the designer, such as sheet metal design for SMEs. Gugel & Schrödel (2010) have developed special CAD tool for feature oriented costing.

Jochem (2010) emphasizes that a forward-looking, holistic quality management approach is required to reduce overhead costs. Not only must the quality of production be improved, but the early phases of product development also must include measures for improving quality. To do this, he describes several analysis and measurement methods, indicators and control factors for the entire value chain that are important.

In the research project 'Cost impact of modularisation KosMo' (Kersten et al. 2012), a holistic approach has been developed for the systematization, structuring and analysis of cost effects. Cost drivers can be identified, and thus cost comparisons be carried out on design alternatives. The 'Modularity Calculator' tool allows such an analysis and comparison, mapping market and cost effects, making complexity manageable and increasing transparency within a company. Accordingly, recommendations can be derived to control the level of modularisation.

Integrating new concept solutions from other technical disciplines extends the functionality and range of solutions. For the assessment of design

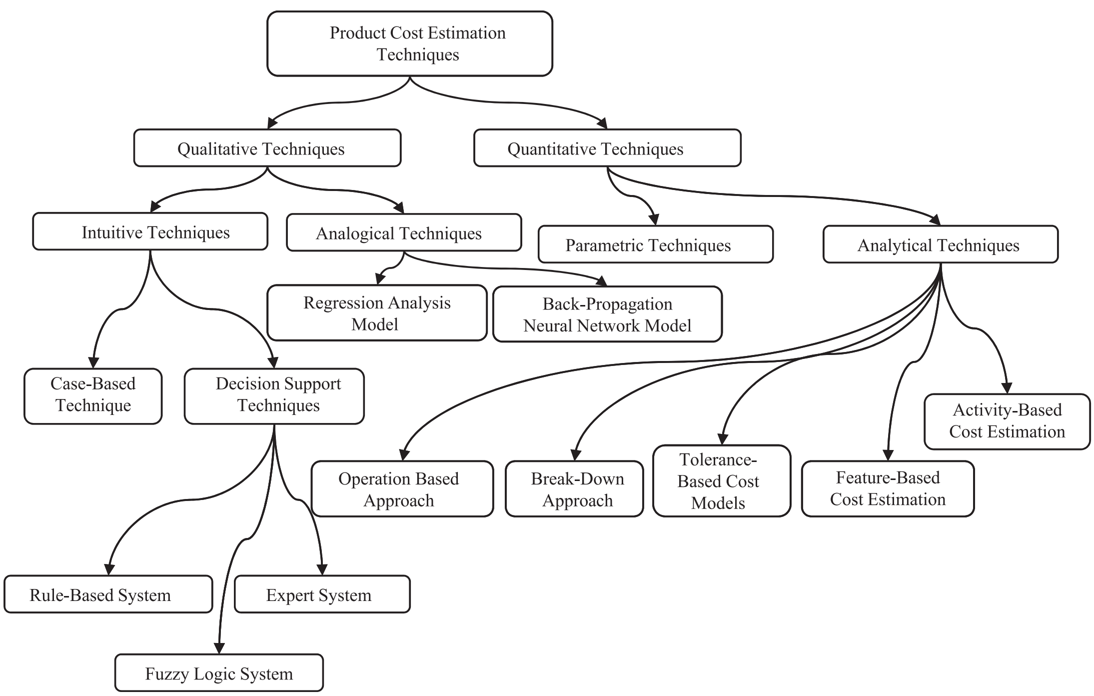

Figure 13: Classification of product cost estimation (PCE) techniques (Niazi et al. 2006).

Product Cost Estimation Techniques				Key Advantages	Limitations
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Case-Based Systems		Innovative design approach	Dependence on past cases
		Decision Support Systems	*Rule-Based Systems*	Can provide optimized results	Time-consuming
			Fuzzy logic Systems	Handles uncertainty, reliable estimates	Estimating complex features costs is tedious
			Expert Systems	Quicker, more consistent and more accurate results	Complex Programming required
	Analogical Cost Estimation Techniques	*Regression Analysis Model*		Simpler method	Limited to resolve linearity issues
		Back Propagation neural network model		Deal with uncertain and non-linear problems	Completely data-dependant, Higher establishment cost
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers can not be identified
	Analytical Cost Estimation Techniques	*Operation-based cost models*		Alternative process plans can be evaluated to get optimized results	Time-consuming, require detailed design and process planning data
		Break-down cost models		Easier methods	Detailed cost information required about the resources consumed
		Cost tolerance models		Cost effective design tolerances can be identified	Require detailed design infrmation
		Feature-based cost models		Features with higher costs can be identified	Difficult to identify costs for small and complex features
		Activity-based cost models		Easy and effective method using unit activity costs	Require lead-times in the early design stages

Figure 14: The PCE techniques: key advantages and limitations (Niazi et al. 2006).

variants, the costs must be estimated, and the balance between acceptable and optimal solutions for all domains must be found.

Zirkler (2010) develops a guide for a trans-domain target costing management. A design structure matrix (DSM) is used to represent the product functions. Using the domain mapping matrix (DMM), partial functions or partial processes are connected with individual components. Similarly, resources and process building blocks can be connected with a DMM. Different product concepts and structures require different partial processes and resources for product realization. The cost of resources can be classified from process building blocks to product components by means of several calculations.

Sandborn (2013) analyses in great detail various cost accounting procedures related to electronic systems. He examines production costs as well as more comprehensive topics like total cost of ownership (TCO). At the same time he describes cost estimation, activity-based costing (ABC) and parametric cost modelling approaches.

Trendowicz (2013) developed a new integrative approach to estimate software costs. He describes how to use CoBRA (an abbreviation of cost estimation, benchmarking, and risk management) by exploring several real-world cases.

Design structure matrix (DSM): A matrix-based tool/method to structure and analyse complex systems/products. The DSM is able to model and analyse dependencies of one single type within one single domain.

Domain mapping matrix (DMM): Represents an advancement of DSMs to allow for the mapping between two domains.

Cost of resources: Resources are, e.g., material, labour, capital, external work, societal aspects.

Total cost of ownership (TCO): Represents total costs for the buyer/owner of a product, including procurement and operating costs.

CoBRA: Method for Cost Estimation, Benchmarking, and Risk Assessment.

Product architecture: Describes how parts/elements of a product are composed and interrelated to each other.

Systems engineering: An interdisciplinary approach and means to enable the realisation of successful systems/products.

System-of-systems (SoS): Applies to a system-of-interest whose system elements are themselves systems; typically these entail large scale inter-disciplinary problems with multiple, heterogeneous, distributed systems (INCOSE 2012).

Cost analysis: Analysis of costs related to a system (e.g. product or project).

Variants: Alternative product or design versions.

Complexity cost: Costs caused by higher product complexity compared to standard products (e.g. additional design, test, material cost, logistic, variants).

Multiple domain matrix (MDM): A meta model matrix representation for modelling whole systems consisting of multiple domains, each having multiple elements, connected by various relationship types. A MDM is built up on DSMs and DMMs.

Multi-valued decision diagram (MDD): Decision diagram where every decision node can represent the number of possible values.

New products, such as offshore wind turbines and electric vehicles, need novel approaches to cost estimation. While expenses can be estimated more or less accurately, they must, however, be validated later, sometimes after several years of experience. Offshore equipment has changed the cost structure of life cycle costs: e.g. helicopter use for maintenance support, environmental influences (e.g. salt water), assessment of business interruption risk and ship collisions (Kaiser & Snyder 2012). Gorbea & Fricke (2009) derived strategic approaches to product architecture based on life cycle costs of (electric) vehicles. The experiences come from, among others, large-scale field trials.

Besides all research in the design for cost sphere aspects on cost types, design related and cost analysis methods one should be aware that cost estimating is also affected by basic human psychology aspects (Prince 2015).

4.3.1 Systems engineering: Modern design methodologies, e.g. systems engineering, contribute to the advancement of design for cost. Blanchard (2009) offers the most extensive general summary within the area of cost management, in the context of systems engineering. Valerdi (2005) presents the tool COSYSMO for estimating cost of systems engineering activities in engineering design, which had not previously been addressed, and examines advanced cost estimation methods and suggests improvements in this field using heuristics (Valerdi 2011). Extensions to the area of systems–of–systems (SoS) can be found (Lane & Valerdi 2005), (Lane 2009), and transfers to the area of human systems integration (Valerdi & Liu 2010). Theoretical basics of systems engineering are employed by Schmied et al. (2015) to provide extended cost analysis options on specific cost behaviour and measures for cost reduction in the early stages of product design.

4.3.2 Complexity management: Complexity cost considerations for mechatronic products started with the study of Braun et al. 2007. Overhead costs of a company accrue many cost elements for variants that are not yet explicitly calculated and analysed. Various studies argue that mastering of variants has a high impact on the reduction of overhead costs. Bauer et al. (2015) provide an approach to estimate the complexity cost caused by changes and variants. They consider 1) changes to existing variants, 2) variants that are substituted by others, and 3) additionally created variants. Their method connects change causes with product architecture, and an impact analysis including complexity cost using multiple domain matrices (MDM). Gleich and Marfleet (2012) have also evaluated the cost caused by variants. They describe, providing several examples, as to the types of overhead costs that can occur, and how these costs can be impacted. Another study by Wildemann (2012) shows the consequences of changes, their causes, and provides average cost values for changes: in a literature review, he found that costs of almost EUR 1,000 to about EUR 7,000 or even up to $10,000 per change are incurred. Browning (2015) presents an overview on DSM literature where also cost aspects are addressed.

4.3.3 Cost dependency models for product configuration: Highly customizable products like cars, are typically directly configured by customers themselves, by means of product configurators offering a set of possible options to choose from. The composition of options is constrained by feasibility rules which arise, e.g., from technical feasibility as well as from marketing strategies.

While calculating the final price for the customer is a fairly simple summation of the options' individual prices, the calculation of manufacturing costs and contribution margins has to account for dependencies between options. For example, adding a television option might be associated with lower costs if a high-end navigation system is already chosen. Since these constraints need to be considered in a configuration space containing an astronomically large number of possible configurations, efficient means are required for representing, analysing and designing such cost dependency models.

Based on the software technology of Soley,[1] a graph-based approach was developed, which builds on multi-valued decision diagram (MDD) (Berndt et al. 2012) and allows to efficiently represent huge configuration spaces in a manageable model, see Figure 15. This graph is constructed considering the constraints between available options and the cost dependencies among them: Every path from top to bottom through the graph corresponds to one valid configuration. Along this path, cost dependencies are considered such that for every configuration, manufacturing costs and contribution margins can be calculated. Based on this representation, systematic studies of cost dependencies are possible, as are sensitivity studies if cost changes are to be analysed.

4.3.4 Integrated value engineering: Integrated value engineering (IVE) is an approach for the

[1] Software available at: www.soley-technology.com.

analysis and optimization of the product cost-value-ratio through the evaluation and design of product structures. The approach combines target costing and value engineering to identify cost reduction and value enhancement potentials in early development phases for mechatronic products. These potentials are derived on the level of requirements, functions and components (see Figure 16) to enable practitioners to focus their initiatives to improve the cost-value-ratio of their products (Maisenbacher et al. 2013; Behncke et al. 2014).

4.3.5 Indirect costs of engineering changes: Customers require more and more individualised solutions. This leads to more and more engineering change projects. Therefore companies, in addition assessing to technical options, must assess all costs resulting from a design change and try to quantify resulting costs. direct costs (material, production) can be estimated quite easily, but indirect costs of design change are not efficient to quantify. A calculation by overhead rates is very expensive, and is therefore only rarely done. Moreover, literature confirms that calculation of overhead rates leads to results of low quality (Coenenberg et al. 2012). In addition, more suited approaches like activity-based costing are costly, and the cost can be estimated only at a great expense of time (Friedl et al. 2013).

In the research project AIDA (Schmied et al. 2015), cost drivers, activities and roles are being linked. A change process model (Figure 17) is developed to quantify the indirect cost of design changes, and heuristic approaches are examined for cost estimation. Figure 17 shows how cost drivers are used to describe the use case of change or change situation. These weighted cost drivers represent inputs for the process model shown in middle of the figure, where a three domain model incorporates the system cost behaviour. The output is a more quantitative distribution of involved activities (partial change processes) and roles (e.g. company departments). With this approach, systematic measures for cost reduction can be applied to the domains cost drivers, activities and roles. For engineering changes the cost drivers are determined by design characteristics, hence be directly influenced by the designer.

Therefore, companies are supported to determine indirect cost of changes more easily. In addition, companies are enabled to select the most cost efficient alternative among various

Change process model: Model for structured analysis of change processes that describe systems behaviour of the three domains: cost drivers, change process activities and involved company departments.

Direct costs: All costs that can be directly assigned to an allocation object or are assigned in a specific application case (e.g. material direct costs).

Indirect costs: Synonym for overhead costs.

Overhead rates: Accounting method where value of indirect costs is approximated by using a company specific percentage of direct costs.

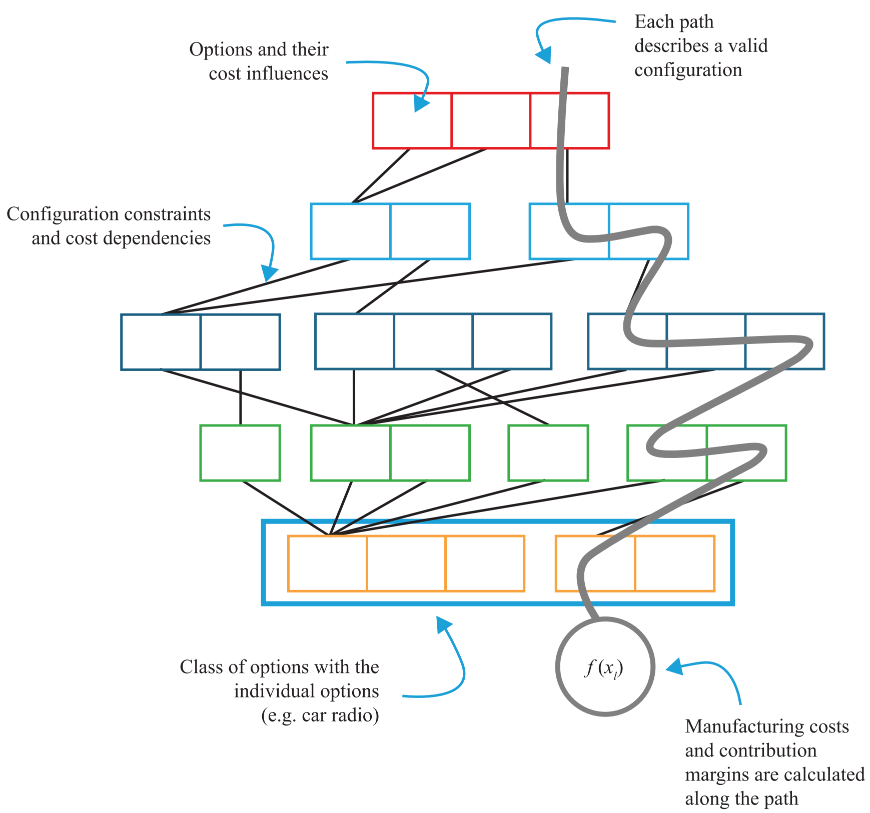

Figure 15: Representation of huge configuration spaces (Soley).

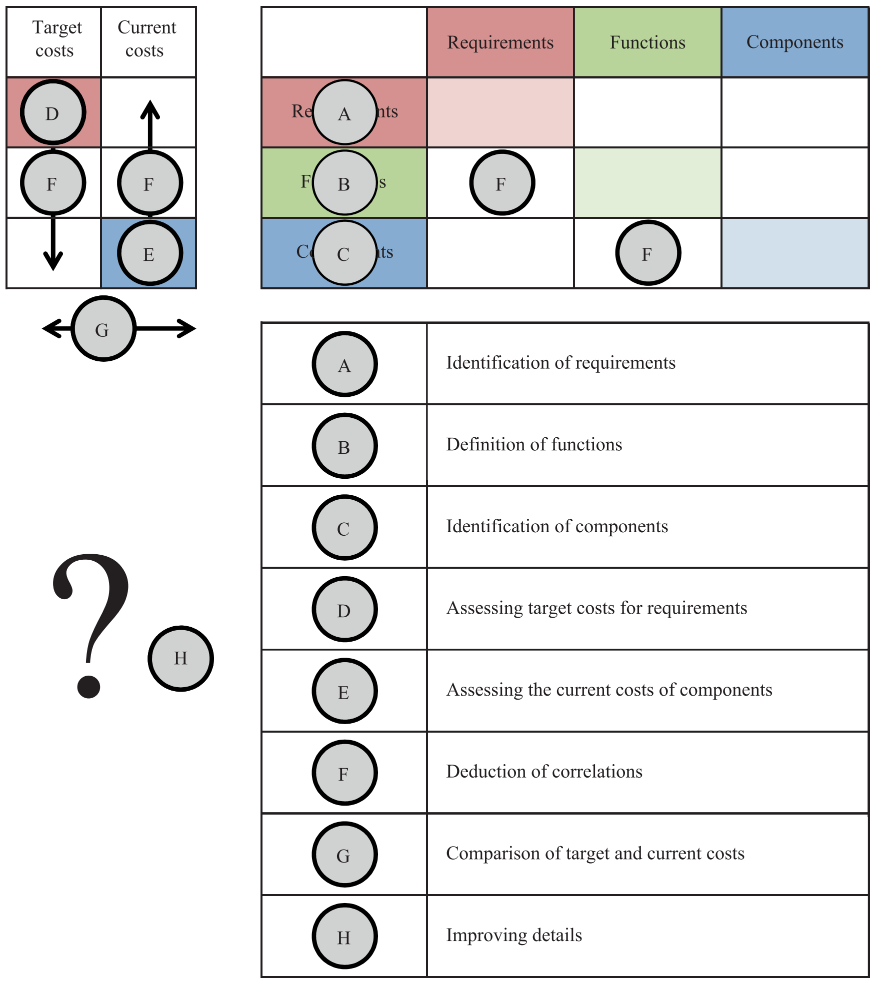

Figure 16: Integrated model for value engineering (Maisenbacher et al. 2013).

design change options and to reduce their own costs. Heuristics are rules of thumb in terms of simple decision rules, using which a still sufficiently satisfactory solution can be achieved with low effort. This is advantageous for SMEs, which have fewer resources, such as personnel capacity and established methods, than large companies have.

Product service systems: Business strategy for companies to offer a mix of products and services.

4.3.6 Software tools: In the field of cost estimation and analysis, a variety of software tools have already been developed. A portion of these were introduced only in individual companies or in specific industries. Such software tools can be applied in different phases of product development, depending on what information about the product already exists.

Open innovation: A new design paradigm that incorporates company external ideas into the innovation process.

A recent research found over 100 tools (Ehrlenspiel et al. 2014, Mörtl 2013). Some of these are commercial tools and are used in industry (e.g. ARIS, Facton, 4cost, KingCost, Mirakon among others). Other tools have been developed at universities (e.g. XKIS, KosKA, CoCoS), and are used occasionally, or not yet, in companies. Shermon (2009) shows the origination of the tools (PRICE, SEER, ACES), which began in the 60s, and their subsequent development.

3D-printing: Manufacturing method to build (print) a three-dimensional object with successive layers of material based on a 3D computer model.

4.3.7 Conclusion and outlook: Service costs have rarely been addressed in literature. product service systems and upgrading approaches in product design have also not yet been fully examined (e.g. Akiyama 1994; Mörtl 2002, Erkoyuncu et al. 2009, Wildemann 2013). New design methodologies or strategies like open innovation reveal the need for cost research. Initial studies have addressed topics like cost/risk evaluations (Gürtler 2015), but there is scope for much more work.

New fields of research are arising and existing ones are expanding. The fast emerging manufacturing technology '3D-printing', also known as 'additive manufacturing', show the typical pattern for cost research when new technology

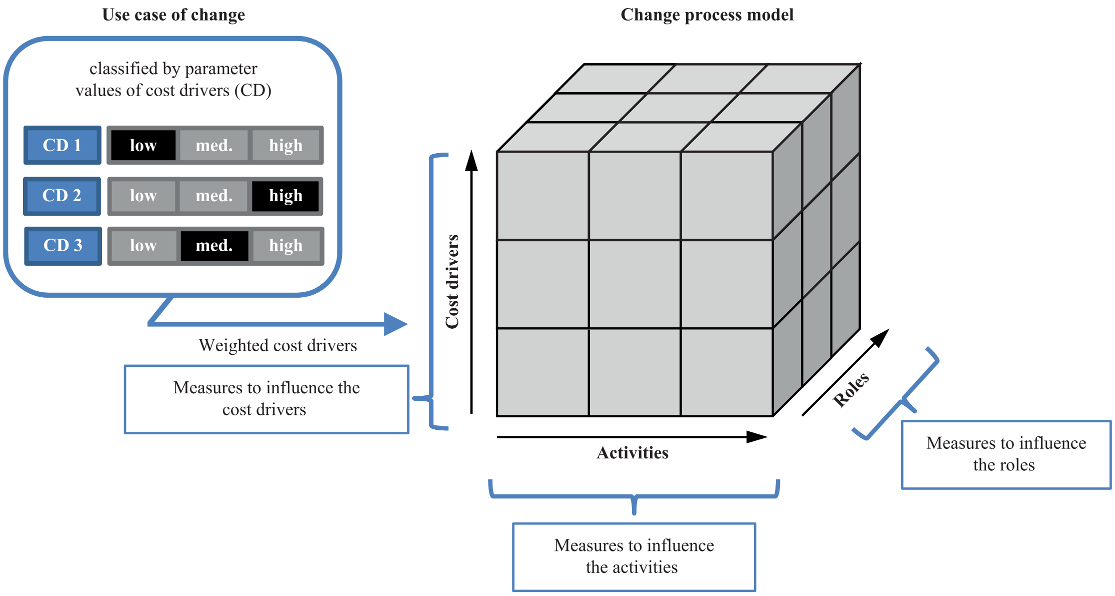

Figure 17: Approach to the derivation of cost reduction measures (Schmied et al. 2015).

becomes available for designers. Accordingly, traditional cost models and cost estimation techniques need to be updated and cost research initiated (Bauer & Malone 2015, Thompson 2015). Similarly, big data applications are also emerging to support design for cost decisions (www.soley-technology.com) and could be a future research focus. The aerospace industry will continue to have a strong need for new cost estimation tools, especially for larger projects (e.g. Kazanowski 1983; Isaksson 2002; Erkoyuncu et al. 2011; Gorbea 2011).

In summary, design for cost research will continue as new design methods, tools and possibilities are created and new uses are recognised with regard to changes in cost structures/types (e.g. new item in product design: service costs), design related aspects (e.g. new design methodologies: open innovation; new technologies: 3D-printing) and cost analysis methods (e.g. systems engineering as a design method applied to cost analysis) as well as combinations of the three areas (Figure 9) on design for cost.

Received 2 October 2015.

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