Abstract: In Engineer-to-Order (ETO) manufacturing the price of products must be defined during early stages of product design and during the bidding process, thus an overestimation of product development (PD) costs may lead to the loss of orders and an underestimation causes a profit loss. What many ETO systems have in common is that the products have to be developed based on different customer requirements so that each order usually results in a new variant. Furthermore, many customer requirement change-requests may arise in different phases of the PD, which is to be considered properly. Thus it is utmost important for ETO systems to have an accurate cost estimation in first stages of the product design and to be able to determine the cost of customer requirement changes in different phases of PD. This paper aims to present a cost estimation methodology as well as a cost estimation model, which estimate the cost of products by relative comparison of the attributes of new product variants with the attributes of standard product variants. In addition, as a necessity in ETO manufacturing, the cost calculation of customer requirement changes in different phases of PD is integrated in the presented method.

Keywords: Cost estimation; Customer requirement change; Engineer-to-order manufacturing

1 Introduction

Increasing competitive pressure urges companies to offer more customized products while reducing the costs and the time-to-market at the same time. This also applies to ETO manufacturing systems with highly customized products. In ETO manufacturing, the production takes place on order and many individual orders are the triggers of the order processing [1]. Furthermore, the end products have to satisfy various customer requirements exactly, so that usually each new ordered product is a new variant [2]. This trend induces a high complexity to the system and increases the number of variants drastically. In ETO manufacturing, an almost precise cost estimation has to be generated for each offer [2] during the bidding process or during the conceptual and preliminary stages of the PD [3, 4].

The situation intensify as the customer requirement change-demands increase during the PD process, which makes new cost estimations necessary [5]. Due to these critical facts, various cost estimation methods and techniques for providing accurate and consistent cost estimates have been developed. Most of these methods have been designed not only to find best possible design solutions but also to achieve the maximum customer satisfaction concerning low-cost, high-quality and in time product delivery [4, 6]. However, it is observed that most of the cost estimation techniques cannot adequately estimate the costs of the requirement changes during the PD process [5]. Following sub sections give an overview on ETO manufacturing and cost estimation in various development stages.

1.1 ETO manufacturing

The initiation of the internal order processing activities can be carried out either by customer orders, through sales expectations or a combination of these two types of triggering. This defines especially the organizational structure and the binding type of the production to the market [1]. Companies that produce their products only after receipt of a customer order are called order-oriented companies. These companies hold no stock with finished products [7]. An extreme case of order-oriented companies are ETO manufacturers, where the PD and production take place only based on specific customer orders and usually according to specific customer requirements and needs. The ETO manufacturers are, in particular, providers of sys-
system solutions, capital goods and individualized products, such as machine tools, production equipment, pumps, compressors etc. [8].

In the first stages of order processing, there is a limited amount of information available for manufacturing-related decisions. To bridge this information gap, expert knowledge and experiences are needed [9]. Hence, the project planning have to be done often based on assumptions [10]. To avoid the risk of high lead times and development costs, ETO manufacturers are trying to avoid radical product innovations as far as possible. Therefore, the new customized products are often designed based on already developed products and system solutions [11].

A customer inquiry initiate the necessary activities to offer processing and subsequent negotiations with the customer [8]. At this stage, it is necessary to respond with an offer to the customer’s request as quickly as possible. The offer should particularly include a cost-covering and competitive price with a rough delivery time [12]. In general, following four problem areas have to be considered for each offer [8, 13]:

- Technical feasibility: The first thing to consider is whether the company can produce the desired product with the specifications mentioned in the customer request. This requires often the feedbacks of design and planning departments.
- Delivery date: The scheduling is often carried out based on estimated data and information as well as practical knowledge. The uncertainties regarding the capacity loads and procurement periods can cause significant supply problems especially with new (innovative) products.
- Price: The cost estimation of the product and the pricing of the offer have to be carried out often only based on historic data. In general, there are no accurate product information available, since the offered product has not yet been constructed.
- Terms and conditions: In addition to price and delivery time, there exists often a set of legally binding conditions for both contract partners. These are, for example, penalties for missed deadlines, payment terms, discounts etc. and must be carefully thought out and formulated.

Figure 1 shows the main steps of a bidding process in ETO manufacturing. These activities are usually carried out in close cooperation with the customer and often in several cycles. Depending on the order complexity and amount, the process can take a few days to several months. As illustrated, the costs will be estimated based on customer requirements and specifications and after technical approval as well as delivery date determination. This completes the proposal for submission to the customer.

![Figure 1: Bidding process in ETO manufacturing, adapted from [3, 14].](image)

In this paper, the focus is mainly on the cost estimation of customized product variants in the offer phase. Furthermore, the cost estimation of changes that arise due to internal or external causes during the order processing, is explained in more detail.

### 1.2 Cost estimation in bidding phase

As the PD progresses, the precision and reliability of PD cost estimation will be increased [15]. However, if the cost estimation can be done during the early stages of product design, designers can reduce efficiently the product cost by modifying the designs to achieve more reasonable cost and performance [16, 17]. Thus, it is highly desirable for companies to use methods and techniques, which increase the cost estimation reliability during the PD planning stage or offer phase. Figure 2 shows the cost estimation dilemma of cost oriented product design. The necessary knowledge for cost evaluation is only in later stages of the PD process available, where the impact on product cost is low.

Cost estimation through expert judgments is one of the main approaches in early projects and PD stages. The estimation will be carried out mainly based on experience from previous projects and often at the macro level. Here
is the implicit expert knowledge the only reliable source in the early stages of the project [18]. By relying on previous experiences and expert judgments, many estimators use previous projects as pattern for the new ones and adapt them to the new requirements [3]. Although the experts’ judgements remain as a valuable and cost-effective approach, but the estimation results are usually very subjective [19] and the quality and repeatability of results depends highly on the expert’s experience.

![Figure 2: cost estimation along the product development process [20].](image)

Generally, one can distinguish between top-down and bottom-up cost estimation methods. The top-down methods are more suitable for cost estimations in early phases of PD, when the information is not yet available in detail. The estimates are usually held at higher levels and are therefore often inaccurate. On the other hand, the estimation process of bottom-up methods begins at the component level or detail level. The aggregating of the estimated costs of the (child) elements gives the cost of the next highest parent element, which finally leads to the cost estimation of the entire product or project [18]. The bottom-up estimations are often conducted based on a work breakdown structure (A WBS dismantle a project into its components). The bottom-up methods are in general more data-intensive and more complex than the top-down methods, but at the same time, they provide more reliable results [18]. Therefore, they can be employed often only in later design phases, when sufficient data is available.

Niazi et al. [6] classified cost estimation techniques into qualitative and quantitative techniques. These primary categories are themselves divided into intuitive and analog techniques as well as parametric and analytical techniques. Qualitative cost estimation techniques utilize the past data and knowledge to estimate the cost of a new product in the early phases of the design cycle when almost no detailed information is available. Based on the comparison analysis, the similarities between a new product and already manufactured products will be identified. Hence, it would not be necessary any more to estimate the cost of a new product from scratch. Even though the qualitative techniques provide only rough estimations, they still offer valuable information to decision makers especially during the design conceptualization. In contrast, detailed product and process information is a prerequisite for the applicability of quantitative cost estimation techniques, which restrict their usability to the final phases of the design cycle. The average obtained accuracy of the main cost estimation techniques is listed in Figure 3.

![Figure 3: Accuracy of the cost estimation techniques, adapted from [3, 21].](image)

<table>
<thead>
<tr>
<th>Cost estimation techniques</th>
<th>Key advantages</th>
<th>Limitations</th>
</tr>
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<tbody>
<tr>
<td>Intuitive techniques</td>
<td>Preliminary stage</td>
<td>-30% to +50%</td>
</tr>
<tr>
<td>Analogical techniques</td>
<td>Conceptual design</td>
<td>-14% to +30%</td>
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<td>Parametric techniques</td>
<td>Conceptual design</td>
<td>-14% to +30%</td>
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<tr>
<td>Analytical techniques</td>
<td>Detailed design</td>
<td>-5% to +15%</td>
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Figure 4 shows typical approaches for cost estimation in different phases of the PD. There are also the key advantages and limitations mentioned. Based on several different factors, such as product complexity, innovation level and novelty, data availability and reliability, existence of a work breakdown structure as well as required estimation accuracy, one or more of these approaches can be

![Figure 4: Key advantages and limitations of the cost estimation techniques, adapted from [3, 6].](image)
appropriate for the cost estimation. To support the decision process, Niazi et al. [6] proposed also a decision support model for selecting the appropriate cost estimation method.

A selected number of appropriate methods and techniques in the first stages of PD will be described in this section. These are “Case-Based Techniques”, “Decision Support Techniques”, “Regression Analysis Model”, “Neural Network Model” and finally “Parametric Techniques”.

The case-based reasoning methodology utilizes the past cost data of previous design cases to generate new estimations. However, it is not applicable without similar past designs [6]. Both similarities and differences between the old and the new products have to be identified. The case-based cost estimation is a robust and feasible method for many companies with similar products. The cost of new products and technologies, however, cannot be estimated with the help of the case-based methods, since no historical data exists [19]. The case-based cost estimation usually depends very closely with the expert judgment together [18]. This approach is useful in reducing the design rework and cost estimation time [22].

The decision support systems (including rule-based systems, fuzzy logic systems and expert systems) are especially helpful for evaluating and selecting design alternatives. They support the experts by providing the stored expert knowledge at different levels of the estimation process. The Artificial Intelligence (AI) is used here to represent and utilize a domain expert’s knowledge and serves as a decision-aid tool [6]. The major limitation of these methods is the great deal of time and high costs for the development and implementation of desired tools.

The regression analysis models use data from previous projects to systematically derive the existing relationships between the product cost and the selected product parameters (as variables). The costs of each cost type, such as material or production costs, will be then determined by separate equations with limited complexity [23]. The regression analysis approach uses the principle of similarity to estimate the cost of new products by using historical data and product parameters [6]. The equations of regression analysis models are constructed based on data, expert knowledge and logic and the assumptions remain often comprehensible [19]. However, the statistically developed formulas are poorly interpretable and it is difficult to draw conclusions from the formula structure. In addition, correct assumptions and current data are necessary to get reliable results. Finally, the acquisition and analysis of data sets are time consuming [23, 24].

Unlike the regression analysis models, the cost estimation logic behind the neural network models is not easy to follow. The models are considered here as black box [19]. Nevertheless, the neural networks have an excellent adaptability for complex, non-linear data [23]. The model can approximate the (hidden) relations between cost-related features and the whole product cost. However, it needs to be trained with data from earlier cases to learn which features most strongly affect the final cost [19, 25]. Furthermore, accurate historical cost data is a prerequisite for the neural network training [25]. Finally, neural networks cannot deliver reliable and accurate estimations in case of radical innovations of very complex products [23, 26].

The parametric models for cost estimation are widespread. They can be used partly also in early stages of development. The parametric model aims to define a relationship between product features and cost. It consists of a set of mathematical relationships (CER¹), rules, assumptions, variables and constants that describe a specific situation [28]. The CER complexity depends on the complexity of the product and the number of variables [19]. Through parametric models, the cost can be estimated quickly and systematically. A major disadvantage of the parametric models is, however, the high development costs for the derivation of the mathematical equations, as well as for the acquisition of the accurate historical data.

Based on the described techniques, several solutions have been developed for cost estimation in ETO manufacturing. However, these solutions are mainly, application- and domain-oriented developed and their adaption for other application domains is not readily possible [3]. Often, the cost estimation solutions offer also a hybrid solution based on two or more estimation techniques to use the advantages of these techniques in combination.

By using the parametric approach, Lackes [29] proposed a variant cost estimation method that fits the companies with a very high number of product variants best. The developed method simulates the purchase decision process and uses product variant characteristics and attributes defined by customers as cost driving attributes. The main advantage of this characteristic-based cost estimation method is the significant reduction of the number of calculation units. However, an accurate assignment of sale-specific attributes (cost driving attributes) to production-specific attributes is a prerequisite. This can be done for example by using configuration and compatibility matrices.

¹ A CER (Cost Estimation Relationship) is a mathematical expression, which correlates the costs with physical, technical and operational parameters or cost drivers [27].
Torres [3] gives a detailed overview of cost estimation methods, techniques and models and their applicability in ETO manufacturing. As a part of his doctoral thesis, he also developed a generic methodology for the creation of cost estimation models in ETO manufacturing. Thus, a cost estimation model can be developed for any industrial areas in a systemic procedure. Based on the presented methodology, he developed exemplary two cost estimation models for two different industry domains (Building Construction and production of steel plants).

1.3 Cost estimation of customer requirement changes

For cost estimation of requirement changes during the PD, two actions are necessary. First, an “impact analysis” must be carried out to analyze and to capture the impact of the requirement changes on the product or system. For this, the internal interactions and chain reactions need to be considered. This takes place usually in the context of requirements management and requirements engineering. Only then, the incurred costs of the requirement change can be estimated through “cost analysis”. The cost analysis is often carried out as a part of the order or project management.

The purpose of requirement management is to ensure that the developed solution meets the customer requirements and expectations [30]. For this, customer needs have to be analyzed and documented as engineering specifications for later design and manufacturing processes [5]. The model-based approaches are beneficial both to link the requirements with each other as well as to link them with the related structural elements. This supports in particular the effective accomplishment of the impact analysis. As the impact analysis of requirement changes is not a subject of this work, it will be no longer described.

The demand for more individualized solutions urges many organizations to change their thought process with regard to requirement change cost estimation [5]. Although requirement changes cannot be always assigned to a specific cost, a single change may affect some requirements or constraints and causes consecutively extra change costs for the organization. This change may have internal impact and affect only one part of the product or it can have some external influences and causes extra changes in other parts of the product [5].

Even though valuable works have been done to manage customer requirements more efficiently while reducing costs at the same time [31, 32], much less attention is paid to the research on cost estimation of requirement changes. As one of the rare works, Oduguwa [5] developed a methodology for “impact analysis” and “cost analysis” at the specification stage. Impact analysis shows the interaction between the product components in the case of requirement changes. Cost analysis determines the cost of the proposed changes. The methodology has been developed for the cost estimation of requirement changes within the automotive industry and its applicability is not examined in other sectors.

Rios et al. [33] developed also a methodology for estimating the incurred costs due to the requirement changes. The method helps to identify the main requirements that have the greatest impact on the product cost. These requirements can affect often development activities, design characteristics and production processes. For model creation, the relationships between the main requirements, the design parameters and the production cost drivers need to be defined. The methodology is developed for the cost estimation of the requirement changes in aircraft building sector. Since only the main requirements and characteristics come into consideration, the method can be implemented with limited effort. However, the quality of the cost estimations is highly dependent on the expert knowledge and it can vary greatly depending on the selected design parameters and requirements. Furthermore, the matrices can become quite quickly unclear, if the considered products and systems get complex.

1.4 Key contributions

This paper focuses on the requirements of the ETO manufacturing systems and proposes a generic development methodology and a cost estimation model. The model integrates the cost estimation of the PD and the cost estimation of the requirement changes along the PD process. The objective is to

- develop a generic methodology for creation of cost estimation models and
- develop a generic cost estimation model for ETO manufacturing.

Both the methodology and the model are generic and can be used for cost estimation in different industry domains of the ETO manufacturing. The cost estimation model helps to

- reduce the PD cost estimation time and expenses during the bidding process,
- reduce the cost estimation time and expenses of the requirement changes and
increase the product cost transparency along the PD process.

This paper is organized as follows. Section 2 describes the major steps of the proposed methodology. Section 3 presents the proposed cost estimation model. In this section, the mathematical formulation of the model will be described. Section 4 illustrates the proposed concept based on an example. Finally, further steps and conclusions are discussed in section 5.

2 Generic development methodology

Figure 5 illustrates four primary steps of the proposed methodology for development of cost estimation methods for ETO manufacturing. The IDEF0 method is used to model the methodology. IDEF0 serves for functional description and graphical representation of systems or processes.

The development methodology is generic and can be used to develop cost estimation models in different industry domains of the ETO manufacturing. The development will be done as a bottom-up approach and based on a Work Breakdown Structure. Thus, the required accuracy of the cost estimations will be ensured. Furthermore, the direct comparison of pre- and post-calculations as well as the exact allocation of requirement change costs will be possible.

The first three steps of the methodology will be discussed in following sub-sections. The final step is the development of the cost estimation model and will be described in section 3.

2.1 Development of the reference structure

The first step of the methodology is the development of the reference structure and its level of detail. This affects the accuracy and complexity of the entire cost estimation process. Because of the project-oriented nature of ETO organizations, an object oriented Work Breakdown Structure fits the needs best. This contains a generic and technically oriented product structure plus extra needed elements such as engineering, project management, testing etc. Its level of detail has to be defined based on the product and project complexities, the required cost estimation accuracy and
finally the available information during the bidding process. All gained information of the next steps will be added to the reference structure.

The WBS will be developed based on current product and portfolio structures and should be structured ideally modular. For this, various structuring and modularization techniques in literature can be found. The reference structure builds also the basis for a reference model, which is imperative for introduction of model-based approaches.

2.2 Specification of cost driving attributes and cost elements

In this step, the main cost driving attributes of reference structure as well as cost elements will be defined. For specification of cost driving attributes, one or more attributes (functional, physical, etc.) will be assigned to each element of the reference structure. The determination of cost driving attributes has to be done in an interdisciplinary team of different departments and divisions in order to ensure the generality and completeness of attributes. The cost driving attributes are a subset of product attributes and can be driven from existing cost calculation tools, available configuration tools or other expert systems. However, it is recommended to limit the cost driving attributes to the main cost differentiators in order to reduce the data maintenance and handling expenses.

Cost elements include all expenses, which are necessary along the PD process. Examples are design (such as mechanic or thermodynamic), material, manufacturing (such as tooling or machinery), assembly, Outsourcing and overheads expenses. Based on the required accuracy and cost splitting policies, cost elements can be structured and applied at finer levels. Furthermore, different cost elements require different detail levels. For example, design expenses will be calculated at higher levels (main nodes and elements) and material expenses at finer levels of the reference structure. Therefore, it has to be defined which cost elements are necessary for each structure element.

The definition of the cost driving attributes as well as the cost elements need to be done in a bottom-up approach. This ensures that double consideration or overlooking of the cost driving attributes or the cost elements will be avoided.

2.3 Definition of standard variants and standard variant costs

The proposed method estimates the cost of new product variants in a relative comparison with standard product variants. The standard variants must be defined for each structure element. Based on the company’s product portfolio and existing diversity, more than one standard variant may be necessary for each structure element. The cost of each new variant will be then estimated by comparing its characteristics with those of the standard variants. Standard variants have the same cost driving attributes as other variants. The only difference is that their attributes have predefined characteristics, whereas the attributes of a new variant can have any characteristic. For example if we define steel “17CrNiMo6” as standard material of a component, the standard characteristic of the attribute “material type” will be steel “17CrNiMo6” for that component. It is advisable to select the characteristics among the characteristics of the most sold variants. It helps to reduce the time needed for variant cost estimation process.

As reference structure elements usually have different complexity levels, each element may have a different number of standard values. For example, the rotor of an industrial electric motor may have three standard values whereas its cover may need only one standard value. As a result, the cost estimation will be more accurate and the data maintenance stays within an acceptable range.

The impact of cost driving attributes of reference structure elements need to be defined clearly in order to facilitate an automated estimation of the variant costs as well as the costs of requirement changes. This will increase the reliability and quality of cost estimations and reduce the calculation time. For instance, the influence of alteration of the material type from “17CrNiMo6” to “16MnCr5” on costs of an element has to be defined. In the proposed cost estimation model, this is formulated as a weighting factor within mathematical equations. It will be illustrated exemplarily in next section.

The final step is the cost calculation of the standard variants, which have been defined in this section. Cost calculation has to be conducted with regard to the predefined cost elements. Based on the product complexity, available know-how, desired accuracy etc., different methods can be used for cost calculation of standard variants. It is just important that the cost of each component have to be calculated in connection with the cost elements in order to gain the required cost structure of standard variants for later comparison. The cost calculation of the standard variants should be also performed bottom-up. At predefined inter-
vals (e.g. every three to six months), the standard variant costs need to be checked and if necessary updated.

3 Cost estimation Model

The cost of new product variants will be estimated through the comparison of attribute characteristics of new variants with the attribute characteristics of standard variants. In case of deviation, the impact of characteristic changes on all affected cost elements will be considered. The characteristic change can affect one or more cost elements. For example, if the material of the mentioned component in section 2 changes to steel “16MnCr5”, this change could increase or decrease the material expenses while other cost elements may stay intact. The total cost of a new variant will be estimated by summation of all expenses.

3.1 Mathematical formulation

Due to the detailed consideration of cost elements and cost driving attributes and also their interactions, the overlooking (or twice consideration) of characteristic change-effects will be prevented. In addition, by breaking down the PD process in various stages, the requirement change costs can be estimated faster and more properly. Finally, in case of multiple feasible solutions in the concept phase, it would be possible to compare their costs more quickly and choose the most economically attractive one of them. To illustrate the proposed cost estimation method, the problem is formulated as follows:

\[
CV^o_{ij} = Cs_{ij} \prod_{k=1}^{K} \alpha_{ijk}^o \quad (1)
\]

\[
CV^o = \sum_{i=1}^{I} \sum_{j=1}^{J} (B_{ij} CV^o_{ij}) \quad (2)
\]

\[
CV^l_{ij} = CV^0_{ij} \prod_{k=1}^{K} \alpha^l_{ijk} \quad (3)
\]

\[
CV^l = \sum_{i=1}^{I} \sum_{j=1}^{J} (CV^l_{ij}) \quad (4)
\]

where

- \( i \) is the index of the reference structure element,
- \( j \) is the index of the cost element “Design, Material, Manufacturing, Assembly, Outsourcing, Overheads, etc.”,
- \( k \) is the index of the cost driving attribute “Material type, Tolerance, Size, Capacity, etc.”,
- \( l \) is the index of the PD process stage “Concept, Engineering, Tooling, Testing, etc.”, when the requirement change request is received,
- \( Cs_{ij} \) is the cost of component \( i \) with standard characteristics for cost element \( j \),
- \( CV^o_{ij} \) is the cost of component \( i \) with new variant characteristics in the offer phase for cost element \( j \),
- \( CV^l \) is the total cost of a new product variant in the offer phase,
- \( CV^l_{ij} \) is the cost of component \( i \) with new variant characteristics in stage \( l \) of PD process for cost element \( j \),
- \( \alpha_{ijk}^o \) is a weighting factor for cost driving attribute \( k \) of component \( i \) and cost element \( j \) in the offer phase (for identical attributes of compared variants it will be set to 100%),
- \( \beta_{ij} \) is a weighting factor for the cost of component \( i \) for cost element \( j \) in the case of repeated order (otherwise it will be set to 100%),
- \( \alpha^l_{ijk} \) is a weighting factor for cost driving attribute \( k \) of component \( i \) and cost element \( j \) in stage \( l \) of PD process (for identical attributes of compared variants it will be set to 100%).

The first equation defines the cost of the structure elements for each cost element. The cost of each element is calculated by multiplying the cost of a selected standard variant by its weighting factors, which represents the characteristic changes of the cost driving attributes. The weighting factor \( \alpha_{ijk}^o \) is used to limit the calculations only to those attributes, which differ from the standard attributes. For example, if the difference in tolerance characteristic of a component causes only 10% more expenses for material procurement and 15% less manufacturing expenses, the \( \alpha_{ijk}^o \) will be set to 110% for material, to 85% for manufacturing and to 100% for all other cost elements. Thus, the total cost of each component will be calculated by comparing its attributes with standard variant attributes.

The second equation estimates the total cost of the new product variant in the bidding phase by adding up the cost of all structure elements. For new variants the weighting factor \( \beta_{ij} \) will be set to 100%, but in case of a repeated order (e.g. from the same customer with the same configuration), the weighting factor \( \beta_{ij} \) will be used to set some cost elements to zero or other values. For instance, the design cost of a repeated order is about 10% of the original design cost, as only a review may be necessary. However, the material cost of a repeated order is still the same and therefore its \( \beta_{ij} \) will be 100%. 

The third and fourth equations re-estimate the cost of the product variant, if one or more customer requirement change during the PD process. The weighting factor $\alpha_{ijk}$ will be used also to limit the calculations only to those attributes, which differ (because of the requirement changes) from the original defined attributes in the bidding phase. In case of a change-request during later stages of the PD process, even a weighting factor of 200% for some cost elements (e.g. material, manufacturing) is possible. The weighting factor $\alpha_{ijk}$ will be set to 100% for those elements that remain intact despite the requirement changes.

A requirement can be a cost driving attribute characteristic (e.g. tolerance, size, material, etc.), which its modification changes directly the product characteristic. It can also be a non-cost driving attribute, which affects indirectly the structure elements. For example, the adjustment of a component weight limit may force a material change or even a redesign of the entire product.

### 3.2 Definition of weighting factors

The weighting factors can be defined by means of regression analysis, analytically derived formulas, empirical studies as well as based on expert knowledge. Considering the required accuracy and effort, the best possible method for determining each weighting factor should be examined and selected. The decision support model of Ni-azi et al. [6] can be used also here to find the appropriate method for each weighting factor. Since the weighting factors have to be defined individually based on best-possible method and there exists more than one standard variant for complex elements, the weighting factors show high accuracy.

In order to automate the cost estimation process and to reduce the response time to new requests, the available weighting factors must be captured and centrally stored and managed (including constant values, equations etc.). Depending on the market dynamics, this information must be also updated at regular intervals (once or twice per year or more, if necessary). The amount of data needed for the cost estimation of each new variant is limited to standard variant costs and weighting factors. This causes a significant reduction in data management time and costs. This applies especially, when the reference structure is mainly restricted to top-level structural elements (system and subsystem level).

The weighting factor for the cost driving attribute "diameter" of a reference structure element may look like as follows:

$$\alpha_{ijk}^o = \left(\frac{d}{d'}\right)^2 \%$$

Where $d$ is the characteristic of the standard variant and $d'$ the characteristic of the new product variant. The weighting factor $\alpha_{ijk}^o$ can then be calculated by using the indicated equation. The weighting factor $\alpha_{ijk}^o$ can also be used for other standard variants of the element (if there exists multiple standard variants for this element). This weighting factor can also be defined according to diameter range for example as follows:

$$d' \leq 450 \text{ mm } \Rightarrow \alpha_{ijk}^o = \left(\frac{d'}{d}\right)^2 \%$$

$$450 \text{ mm } < d' \Rightarrow \alpha_{ijk}^o = \left(\frac{d'}{d}\right)^{5/3} \%$$

Although the weighting factors $\alpha_{ijk}^l$ for requirement change can also be managed and stored in central databases, it makes more sense to document only the equations, rules and change impacts as well as the important procedures. This is because the weighting factors must be considered separately in various PD stages; therefore, there will be too many weighting factors $\alpha_{ijk}^l$ for requirement change. Moreover, most of the weighting factors will be used rarely so that there maintenance is not necessary or reasonable. Thus, the discrete weighting factors (not the rules and equations) can be determined by experts, just as required.

### 3.3 Quality requirements on the cost estimation model

Torres [3] defines “Accuracy”, “Transparent description of the cost structure”, “Adaptability” and “Applicability in complex products” as essential requirements on a generic methodology to create cost estimation models for ETO manufacturing. According to Torres, these requirements will be used to evaluate the proposed methodology and the cost estimation model presented in this work.

- **Accuracy**: A general definition of the minimum required accuracy in different applications is not usually possible. However, the model can be created depending on the required accuracy. The influence factors are the reference structure, number of cost driving attributes, number of cost elements as well as
number of standard variants. Furthermore, because of the hybrid development approach, each weighting factor can be defined by using the best-possible technique. This affects greatly the accuracy of the model.

- **Transparent description of the cost structure**: The definition of cost elements and reference structure as well as the bottom-up approach for model development ensure the transparency of the cost structure. This true both in bidding phase and along the PD process.

- **Adaptability**: The proposed model can be quickly extended or adjusted in response to external influences (new technologies, cost elements, processes etc.). The weighting factors can be updated frequently based on newly acquired knowledge.

- **Applicability in complex products**: Due to the generic development methodology and generic cost estimation model, the proposed model can be used in different industrial sectors of ETO manufacturing. The complexity of the products will be also more manageable by using unified structures and standardized procedures.

The increasing transparency of the cost structure and the generic applicability of the model are the main contributions of the proposed cost estimation model and development methodology.

### 4 Case example

The proposed model is developed as a part of a concept study carried out within a joint project of the university Duisburg-Essen and the Business Unit PG DR of Siemens AG. The Business Unit PG DR is a global provider of compressor solutions. The engineering and manufacturing of compressor trains are distributed in multiple locations worldwide in order to offer the customer- and market-specific solutions. The compressor solutions are mainly customer-specific designed, manufactured, tested, delivered to the customer and subsequently put into operation. The compressor trains can be used for example in the chemical and petrochemical industry, in oil and gas industry and in refineries. Figure 6 shows a compressor train consisting of an electrical motor as drive, a radial-gear Compressor and the necessary periphery elements.

This paper proposes a generic cost estimation model, which is applicable in different domains of ETO manufacturing. The developed model will be illustrated in this section based on a sample pump system. All values and measures are dummy values and do not reflect any real proportion.

Figure 7 shows a simplified structure of a pump system. It consists of a pump, a drive and other periphery elements necessary for various industries and application areas [34, 35]. For example, a pump system can be used as a lubrication system in a compressor train, which is one of the key periphery elements. As represented, the detail level of the “reference structure” varies. While some elements need to be considered in more detail (e.g. pump), others can be at assembly level (e.g. cleaning facility). It shows, among others, the needed precision for cost estimation and the probabilities to influence the development costs.

Table 1 shows the “reference structure” with all required information for the cost estimation. As apparent, each element has none, one or more “cost driving attributes” and may have one or more “standard variants” with standard characteristics. The attributes are linked to the “cost elements” via a matrix, which defines whether a relation exists or not.

Table 2 illustrates the cost estimation process based on a Rotor ($i = 1$). Here two cost elements are chosen: Material ($j = 1$) and Manufacturing ($j = 2$). In addition, the three attributes Diameter ($k = 1$), Material type ($k = 2$) and Surface finish ($k = 3$) are taken into consideration. Based on attributes and characteristics, we may have equations or constant values for the weighting factor $\alpha_{ijk}$. For example, the weighting factor for the attribute “Diameter” and the cost element “Material” is an equation such as $\alpha_{111} = \left(\frac{j}{n}\right)^2\%$, but the weighting factor for the attribute “Surface finish” and the cost element “Manufacturing” is a constant value such as $\alpha_{213} = 97\%$. The expense of each cost element will be calculated by multiply-
which defines whether a

\[ \text{Product} = \prod M \sum \text{Cost} \]

the same procedure as product

\[ \text{Cost} = \alpha \cdot \text{Est} \]

cost driving attributes and cost elements are clearly visible and

\[ \sum \text{Piping} = 100\% \]

\[ \times \text{Radial} = 110.6\% \]

81%
Pump system

\[ \text{Pump} \]

Table 1: Reference structure vs. cost elements.

Table 2: Cost estimation of a new rotor variant.

![Diagram of equipment line structure of a simplified pump system.](image)

**Table 1: Reference structure vs. cost elements.**

<table>
<thead>
<tr>
<th>Reference Structure</th>
<th>Cost Driving Attributes</th>
<th>Standard Variant 1</th>
<th>Standard Variant 2</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump System</td>
<td>Application</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environment</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluid total</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>Type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flowrate</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>Diameter</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface finish</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Gear Shaft</td>
<td>Type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fundament</td>
<td>Type</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Material type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Cost estimation of a new rotor variant.**

<table>
<thead>
<tr>
<th>Structure Element</th>
<th>Cost Driving Attributes</th>
<th>Standard Variant</th>
<th>New Variant</th>
<th>Cost Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>d=300mm d=350mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material type</td>
<td>P265GH P265GH</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Surface finish</td>
<td>A</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>97%</td>
<td>97%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>94%</td>
<td>94%</td>
<td></td>
</tr>
</tbody>
</table>

Weighting factor: \[ \alpha_i \]

Standard variant costs: \[ C_{\text{std}} \]

New variant costs: \[ C_{\text{new}} \]

Total cost of rotor: \[ \sum C_{\text{new}} \]

\[ \sum C_{\text{new}} = 6.876 \text{ €} \]

Figures 7: Equipment line structure of a simplified pump system.

Table 1: Reference structure vs. cost elements.

Table 2: Cost estimation of a new rotor variant.

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<tr>
<td></td>
<td>Environment</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluid total</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>Type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flowrate</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pressure</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>Diameter</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface finish</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Gear Shaft</td>
<td>Type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material type</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>Material type</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

ing all weighting factors of this cost element with the standard variant expense \( C_{V_{ij}} = C_S \prod_{k=1}^M \alpha_{ijk} \). The new cost of the Rotor will then be gained by adding the expenses of all cost elements. The total product cost will be derived by
adding the costs of all elements of the reference structure

\[
Cv^\alpha = \sum_{i=1}^{I} \sum_{j=1}^{J} (\beta_{ij} Cv^\alpha_{ij})
\]

For cost estimation of requirement changes, the impact analysis and technical analysis is necessary to find the new product characteristics. This defines also the new customer specification. The new product cost \(Cv^l\) will be estimated with exactly the same procedure as illustrated in the previous step and table 2. However, in this case the new product characteristics after change-request will be compared with the characteristics of the product variant in the offer phase in order to estimate the cost of the modified elements \(Cv^l_{ij} = Cv^\alpha_{ij} \prod_{k=1}^{K} a^l_{ijk}\) and the total product cost after the change-request \(Cv^l = \sum_{i=1}^{I} \sum_{j=1}^{J} (Cv^l_{ij})\). The weighting factor \(a^l_{ijk}\) will be defined by considering the stage of PD in which the change-request is received.

5 Conclusions

This research proposes a generic development methodology and a cost estimation model, which integrates the cost estimation of the PD and the cost estimation of the requirement changes along the PD process. It was intended to:

- develop a generic methodology and a generic model for cost estimation in ETO manufacturing systems,
- increase the cost transparency and accuracy of both product variants and requirement changes,
- increase the possibility to find the best economically attractive solution in the concept phase,
- reduce the PD cost estimation time in the offer phase (during the bidding process) and the reaction time to requirement change-requests.

Decomposition and break down of complex costing structures to the finest necessary level with simultaneous simplification of costing procedures are major contributions to increase the cost transparency. As a result, the interconnections between reference structure, cost driving attributes and cost elements are clearly visible and highly standardized, which makes the overlooking or double calculation of product costs and requirement change costs in any stage of the PD impossible.

Although various methodologies for cost estimation during the offer phase or bidding process exists, the possibility to estimate the requirement change costs with the same procedure as product costs makes the proposed method more remarkable. This reduces the data handling and maintenance costs to a minimum and help the organization keep track of the requirement changes and their effects on the entire product. Furthermore, the direct comparison of pre- and post-calculations will be possible. Consequently, this makes the requirement change costs more transparent.

In future researches a model-based integration of the proposed cost estimation model in variant and configuration management systems needs to be investigated. Furthermore, the integration of the impact analysis of requirement changes is imperative for efficient cost estimation of requirement changes. Finally, comprehensive case studies based on real test cases and values need to be conducted to develop case-specific models.

References


