METHOD FOR REFERENCE-BASED MANUFACTURING COST ESTIMATION – EVALUATION STUDY USING A PROTOTYPE

Hellweg, Fynn (1,2);
Cacaj, Ardian (1);
Haneke, Simon (1);
Albers, Albert (2)

1: Robert Bosch GmbH, Robert-Bosch-Campus 1, 71272 Renningen, Germany;
2: IPEK - Insitute of Product Engineering at Karlsruhe Institute of Technology (KIT), Kaiserstraße 10, 76131 Karlsruhe, Germany

ABSTRACT

Within product development, manufacturing cost estimation provides a sound basis for design and management decisions. This secures companies profitability, but the effort is high and deep knowledge at the interface of design, manufacturing and costs is needed. These issues can be eased with automation enabled by semantic technologies. Therefore, the authors developed a method for reference-based manufacturing cost estimation and created a prototype. This research evaluates the method and the prototype. Observation, interview and questionnaire were conducted with ten experienced cost engineers at a large German manufacturing company.

Based on its results, the study shows the methods contribution to lower estimation effort, while the impact on transparency and the knowledge base was only partly verified. The method steps show different automation potential, so an incremental automation should be considered. Even though semantic technologies show high potential for identifying reference system elements in this study, the limiting factor for automation in manufacturing cost estimation remains the low availability of product and manufacturing information and missing knowledge of its connection within product development.

Keywords: Design costing, Ontologies, Evaluation, Reference system element, Model of PGE

Contact:
Hellweg, Fynn
Robert Bosch GmbH
Germany
fynn.hellweg@de.bosch.com

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1 INTRODUCTION

A major success factor for companies is profitability (Ansoff and Sullivan, 1993). Rising cost pressure in a difficult market situation forces companies to actively manage their product costs. An example is the fast-growing electromobility market. Manufacturing cost estimation is used early on for high-volume products to support cost efficient product development. Here, it is key to keep the estimation effort low while increasing the transparency in terms of detail. The availability of profound product and manufacturing information and the knowledge of its relation is essential. References, for example similar components, are used when available. However, information is often not stored in a structured way and of bad quality, for example in local documents, not machine-readable and without connection to the product. Though, the knowledge of its correspondence is often limited to experienced domain experts. To improve those issues, a semantic technology method for reference-based manufacturing cost estimation and a prototype were developed by the authors (Hellweg et al., 2023). This research evaluates the method and the prototype with an interview study in corporate setting.

2 STATE OF RESEARCH

2.1 Modell of PGE

According to Albers et al. (2015) all products are developed based on references. The corresponding model of PGE – Product Generation Engineering classifies new products and product generations by the share of newly developed and carried over subsystems. This helps handling risks and costs (Albers et al., 2014). The reference system is the collection of all reference system elements and working as information source for the system in development (Albers et al., 2019). Reference system elements originate for example from competitive products, predecessors, R&D projects or university research (Richter et al. 2019). A methodological deficiency exists at identifying reference system elements. Therefore, a process model supporting the search for relevant reference system elements was derived by Richter et al. (2019). Additionally, Albers et al. (2022) see the need for methods and tools supporting systematic reuse of product and production system-related knowledge and their interdependencies. Therefore, they introduce the approach of Product-Production-CoDesign (PPCD).

2.2 Manufacturing cost estimation

Cost estimation is a cost predicting method based on preliminary data and assumptions (Mörtl and Schmied, 2015). It is part of Design to Cost (Michaels and Wood, 1989). Niazi et al. (2006) give an overview including advantages and limitations of cost estimation techniques. This research focusses on reference-based, bottom-up manufacturing cost estimation as a combination of case-based qualitative technique and operation-based quantitative technique (Hellweg et al., 2023). Manufacturing cost estimations sum up material costs and manufacturing costs (Horsch, 2018). Detailed product, manufacturing, and cost information as well as the knowledge of interaction between those are used to calculate (Horsch, 2018). Within development and design most of the costs are set, so manufacturing cost estimation should happen within product development (VDI, 1987). Benefits in manufacturing cost estimation by using reference system elements were identified in an interview study (Hellweg and Behrendt, 2021). As the usage of reference system elements depends on personal networks and experience (Hellweg and Behrendt, 2021) a semantic technology supported method was proposed by the authors (Hellweg et al., 2023). Mandolini et al. (2020) and Voltolini et al. (2019) also apply semantic technology to the manufacturing cost estimation domain by identifying and using references.

2.3 Method and prototype

Method for reference-based manufacturing cost estimation

The method (Figure 1) is based on the manufacturing cost estimation ontology, developed as part of a case study on the availability of product and manufacturing information in practice (Hellweg et al., 2022). The development was guided by the model of PGE-Product Generation Engineering and took place at research and development of a large German company. Based on the ontology a knowledge graph was instantiated with product and manufacturing information from gear shafts of electric axles.
The method contains of six steps which guide through manufacturing cost estimation of a component (Figure 1) (Hellweg et al., 2023).

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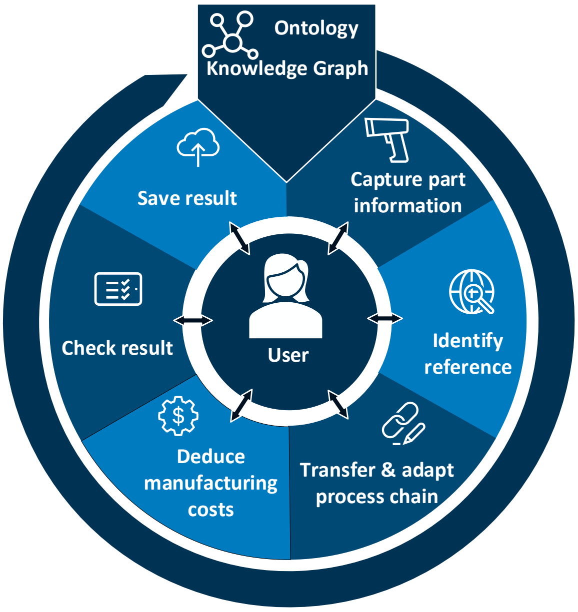

Figure 1. Method for reference-based manufacturing cost estimation (Hellweg et al., 2023)

Prototype

The method, together with the knowledge graph implementation of Hellweg et al. (2022) was also used as starting point for the prototype. The prototype implementation of Hellweg et al. (2023) consists of a graphical user interface (GUI) and was realized with python. The prototype supports the cost engineer with the six corresponding method steps (Figure 1).

In a first step, a STEP-file with included product and manufacturing information (PMI) is automatically read to provide the required product information. Secondly, to identify a reference system element, a knowledge graph query is performed. From the knowledge graph, the manufacturing process chain of the reference system element is retrieved in the third step. Based on the process chain, manufacturing costs are estimated in the fourth step by process specific modules. The fifth step serves to verify the results. Finally, in the last step, the proposed process chain can be stored in the knowledge graph to further enhance the knowledge base. The prototype was developed for gear shafts of electric axles, where examples are available.

3 RESEARCH DESIGN AND USED METHODS

This research is based on the Design Research Methodology (DRM). It evaluates the reference-based manufacturing cost estimation method developed by the authors (Hellweg et al., 2023) and follows the steps of a descriptive study II (DS-II) (Blessing and Chakrabarti, 2009):

- *Reviewing existing documentation* includes the work on literature and the description of the method and prototype (2 State of research).
- *Determining the evaluation focus* results in the evaluation criteria (3.1 Research gap and questions).
- *Developing the evaluation plan* is supported by the Question-Method-Matrix (3.5 Evaluation methods)
- *Undertaking the evaluation* is guiding the evaluation with observation, interview, and questionnaire. This leads to the results (4 Results).
- *Drawing conclusions* is the last step considered in the discussion (5 Discussion).

3.1 Research gap and question

Other authors also apply semantic technology to manufacturing cost estimation (Voltolini et al., 2019; Mandolini et al., 2020). However, they lack a consistent use of references, here provided by reference system elements in the model of PGE. Additionally, only initial evaluation was carried out and research lacks broader evaluation. To better understand and validate the effect of the developed method and prototype this research is guided by two research questions:

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- *How should the developed method be evaluated?*
- *What is the impact of the support on profitability through calculation effort, transparency and knowledge availability?*

Figure 2 shows the intended impact of the developed support. A positive impact on profitability is seen through four success factors. Those success factors are influenced by three measurable success factors. The main impacts between the method, the success factors and the measurable success factors are to be evaluated in this study.

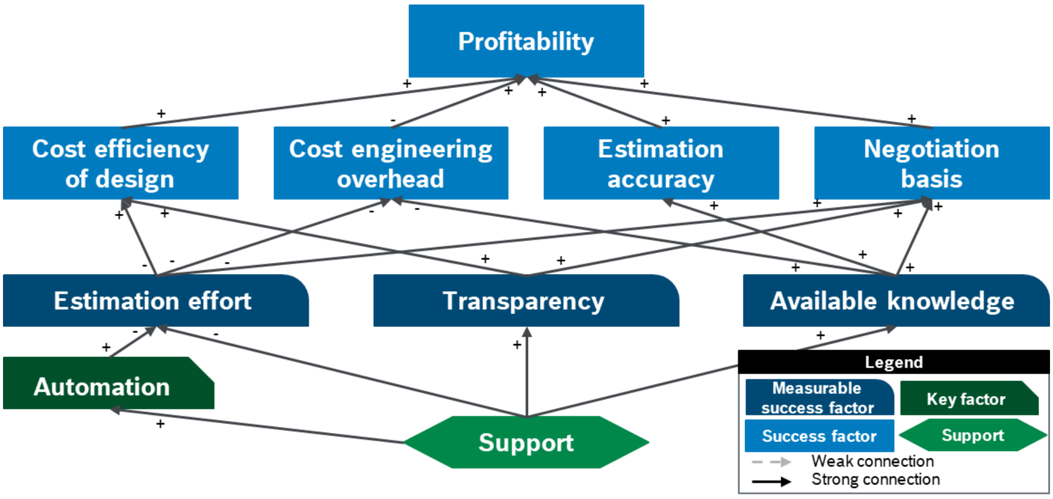

Figure 2. Intended impact model according to Blessing and Chakrabarti (2009) in (Hellweg et al., 2023)

Focus is set on automation for reducing the calculation effort. Here, the prototype helps to evaluate the automation potential of the process steps. A prototype is used to support the method usage and measure the implementation potential of the method. Moreover, it helps to evaluate the automation potential as well as the automation effort of the process steps since automation is the enabler for the elimination of manual effort for frequently used components and a faster availability of cost information.

Table 2: Success and application criteria

E1	The method reduces the cost estimation effort in early phase of product development projects.
E2	The method favours the transparency of costs.
E3	The method favours the use of existing knowledge.
A1	The method is easy to use for cost engineers.
A2	The method is understandable for the cost engineer.
A3	The method is structured in reasonable steps.
A4	The method is transferable to other product and manufacturing fields.

Three types of evaluation criteria are distinguished. Success evaluation (E1-E3), application evaluation (A1-A4) and support evaluation (S1-S6). The success evaluation (Table 2) intends to evaluate the usefulness of the support, i.e., the degree to which the support is successful in achieving the formulated goals. The application evaluation (Table 2) focuses on the assessment of the usability and applicability of the support, based on the desired values of the key factors. (Blessing and Chakrabarti, 2009).

Support evaluation is a continuous test performed throughout the development, i.e., at all stages of the DRM. Here, the six method steps (Figure 1) are used as support evaluation criteria (S1 - S6). It is to be evaluated based on the level of automation.

3.2 Research environment

This study was carried out within cost estimation of a large German automotive supplier. There, product, manufacturing, and cost knowledge is available as well as exemplary information on different components. While the method can be used for a diverse set of components, the prototype was developed with a limited usage scope due to capacity. The prototype is set in the field of electric axle gear shafts. Gear shafts as examples have a wide variety and cost impact on system level. For the evaluation, cost engineers with different product and experience background were chosen. Cost engineers are also the intended user group for the method.

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To test the evaluation study, two pre-interviews were conducted with participants who were not interviewed later in the original study. Ten participants conducted the evaluation study (int1-10). The majority of these work in the subject area of cost engineering, while one participant works in project management and another in sustainability. 50% of the participants show a work experience between 10 and 19 years. 30% have work experience of 20-29 years.

3.3 Evaluation methods (question-method-matrix)

The question-method matrix (Table 3) was used to answer the first research question.

Table 3. Question-Method-Matrix: according (Blessing and Chakrabarti 2009) efficient and effective methods for research aspects. Selected methods are outlined.

Type of evaluation criteria	Observation		Simultaneous verbalisation		Questionnaire		Interview	
Success evaluation	✓✓		✓		✓✓		✓✓	
	R	P	R	P	RR	P	RR	P
Application evaluation	✓		✓		✓✓		✓✓	
	RR	P	RR	P	RR	P	RR	P
Support evaluation			✓		✓✓		✓	
			RR	P	RR	P	RR	P

Questionnaire

The questionnaire was used to collect the thoughts, beliefs, opinions, and reasons from the experts about the method as well as the prototype. It is divided into five parts. The first part asks general questions about the person. The second part deals with the method, the third part with the prototype. The questions focus on the previously derived criteria (Table 3) regarding the measurement of success (E1-E3) as well as the evaluation of the application (A1-A4). The characteristics were measured using a five-point Likert scale from 1 = disagree to 5 = agree completely. For the support evaluation, the effort and benefit of automation, was asked in part 4 and 5 of the questionnaire. This leads to quantitative data, handled with care, as only ten questionnaires were evaluated.

Interview

The interview prepared for the study can be classified as a standardised open-ended interview according to Blessing and Chakrabarti (2022). The interview contains seven questions and leads to qualitative data. The first question relates to evaluating the process chain set up by the prototype. From the second to the fourth, the strengths, weaknesses, and risks of the method were discussed by the participants. The fifth aims to ask the participant about his or her understanding of transparency. Parts 6 and 7 asked for the acceptance of the prototype on behalf of the participant, but also on behalf of all potential users, and on the willingness to share their knowledge, which is one important aspect of the method. The interview part was recorded with a recorder with the consent of the participants for later analysis but cannot be published due to internal content.

Inductive category development, an analysis technique by Mayring (2010), was used for the interview evaluation. The aim is to reduce the expert interviews to the essential aspects to develop a category system that represents the material in an abstract way.

Observation

Observation notes were taken during the study. This was done to include inquiries by the participants in the interpretation. For example, questions regarding the prototype. Another observation focus was time measurement. The participants were asked to draw up a process chain for a component. After the introduction of the prototype, the participants were allowed to use the prototype to perform a supported estimation for the same component. These two tasks were timed separately.

4 RESULTS

All participants were able to provide answers to each question in the interview and completed the questionnaire with a 100% response rate in the given time. In addition to the positively worded questions in the questionnaire, negatively worded questions were also added for each criterion to reduce the response dispersion (Figure 3). The negative questions were inverted to check the overlap with the positive questions.

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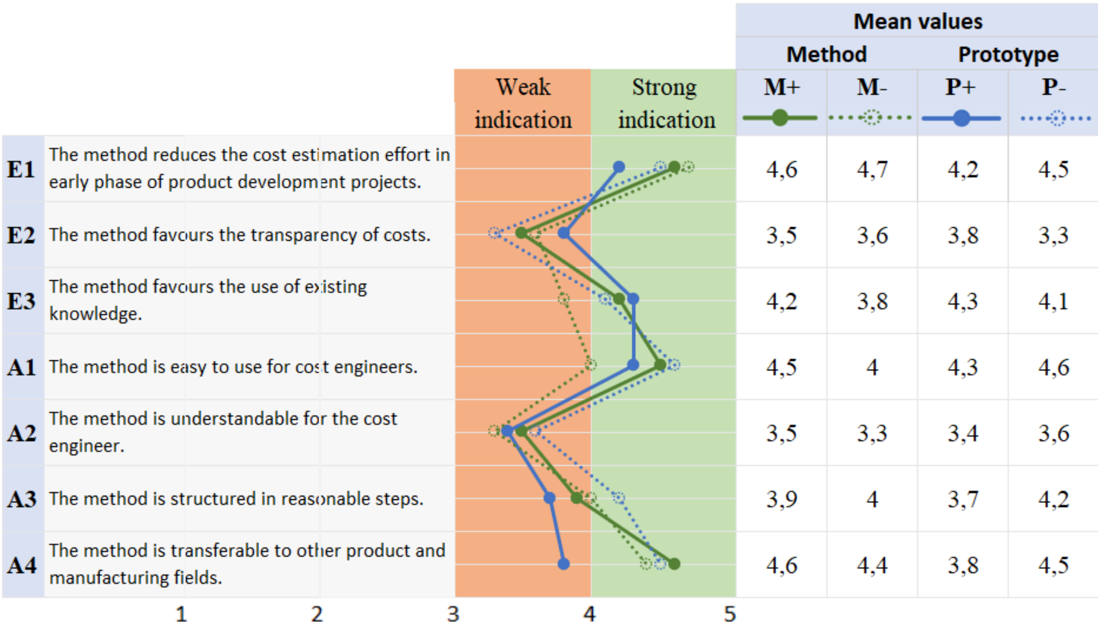

Figure 3: Polarity profile of the results from the questionnaire

4.1 Estimation effort

When discussing the method, all participants stated that the method is a good support for them (Figure 4, left). It provided "quick rough statements about the possible process chains" (Int1) and thus enables "non-experts" also to achieve results (Int 4). Furthermore, 8 participants stated that the effort was reduced (Figure 4, left). Int5 said that "within a short time, a cost model was created for which it would have taken half a day [with the current costing tool]." This statement is also supported by the questionnaire with E1. The results clearly show that the effort is reduced by both the method and the prototype, as the mean values are in the range of strong indication (Figure 3). As a weakness, 90% of all participants mentioned that a plausibility check is necessary (Figure 4, right), since especially "non-experts" run the risk of "misjudging the order of the process chain" (Int1) and "adopting results without reflection" (Int2).

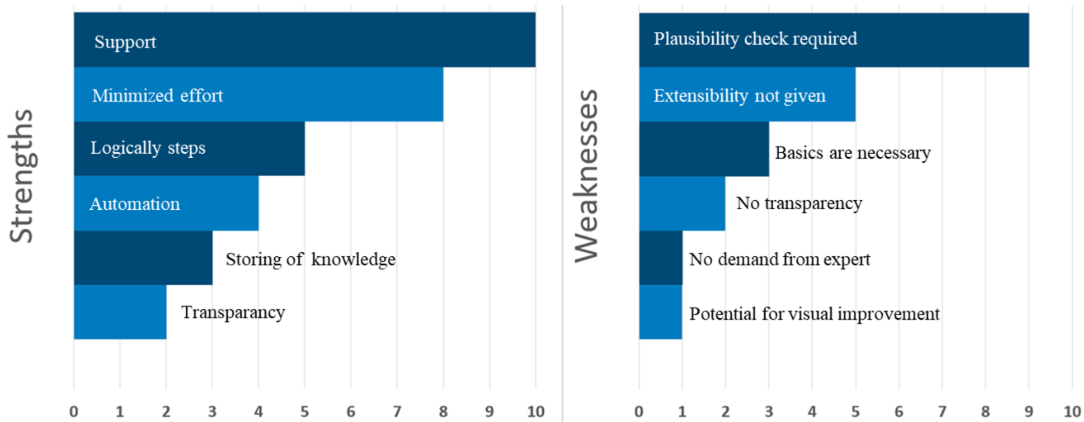

Figure 4: Strengths (left) and weaknesses (right) stated in the interviews.

Four participants mentioned automation as another strength (Figure 4, left). Int6 justified this with the fact that "possible typing errors can be avoided". Automation is the enabler for minimizing effort, since according to Int4 "duplication of work is avoided by identifying similar components". Using the prototype, experienced users create a process chain with cost estimation, in under one minute.
Within the study, a mean value of 7.15 min was detected for manual set up of the process chain. This leads to a time saving of 715%. However, the time recording regarding the manual setup of a process chain and the setup of a process chain with the prototype is not fully comparable since there was a considerable need for discussion and further questioning within the study. Additionally, the manual set up did not consider a cost estimation, which requires additional time and knowledge.

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4.2 Transparency

Transparency in this context means the breakdown of the calculation of a component and its premises. The positive influence of the method on transparency was confirmed by 2 participants in the interview, while 2 participants stated that the prototype prevents transparency in the calculation. In the questionnaire, the statements regarding E2 have a weak indication (Figure 3). In addition to that, the results of the positive questions show that the transparency of the method received lower agreement than the prototype. The inverted negative questions show the opposite.

4.3 Available knowledge

The methods potential to identify helpful references and therefore enlarge the available knowledge was confirmed as a strength by 3 out of 10 participants (Figure 4, left). However, also 3 participants stated necessary requirements of the method as a weakness (Figure 4, right), such as "developing a balanced knowledge base" (Int 4). The prototype is in the range of strong indication for E3, while the method only has a weak indication due to the low mean value of the negative question.

4.4 Application

The questionnaire confirms a strong indication with A1 that the method is user-friendly (Figure 3). However, the focus of the result for this category is mainly on the prototypes and the realization of automation. 60% fully agreed with the usability of the method.

Int5 stated "comparability" as a strength, because "you use databases to work with function comparison". The questionnaire shows a weak indication for A2 (Figure 3).

The influence of the prototype on automation is also explained by the results of A3. However, the positive questions show a weak indication, while the negative questions show a strong indication (Figure 3). In the interview, 50% concluded that it has logical process steps (Figure 4, left) because "it corresponds to the process of a cost engineer"(Int2).

Extension is not easily possible because "new technologies are not considered because they are not stored in the Knowledge Graph" (Int1) and "various alternative process chains are not available" (Int8), which was stated as a weakness by 5 out of 10 participants (Figure 4, right). The questionnaire, on the other hand, shows that the method is transferable to other product and manufacturing fields. Regarding A4, one outlier can be identified regarding the prototype (Figure 3).

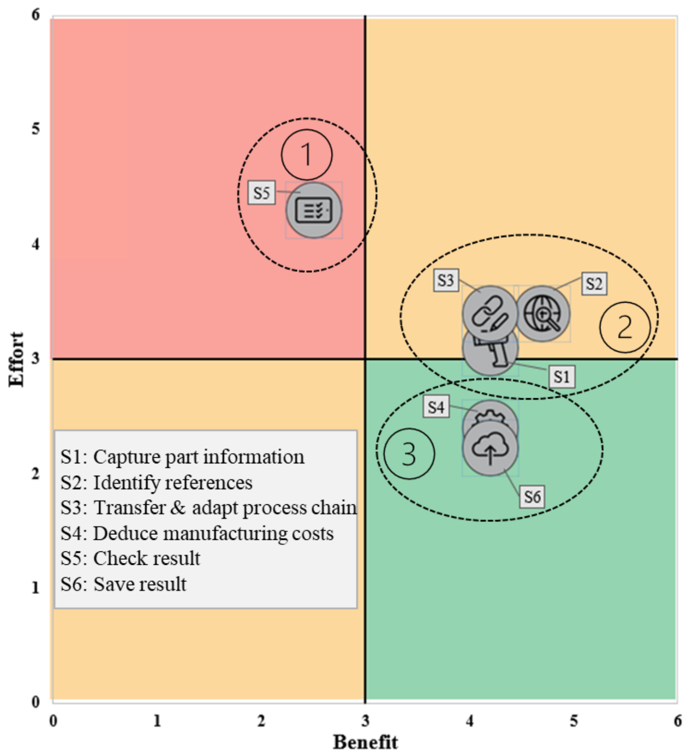

Figure 5. Automation potential as relation of estimated effort and benefit of automation of the six reference-based manufacturing cost estimation method steps

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4.5 Effort / Benefit of automation

The results of the effort/benefit survey of process steps S1-S6 can be seen in Figure 5. The diagram is divided into three colour areas, indicating the automation potential as relation of effort and benefit:

- **Red** indicates low automation potential with high effort and low benefit.
- **Yellow** indicates medium automation potential with either high effort and high benefit or low effort and low benefit.
- **Green** indicates high automation potential with low effort and high benefit.

There are three clusters. The first cluster with process step S5 with the lowest automation potential is in the red field. Cluster number two is in the yellow field, near the border of the green. That means that the steps S1, S2 and S3 show a relatively high benefit, but the automation effort is still moderate. The third cluster is in the green area, where steps S4 and S6 have the best effort/benefit ratio.

5 DISCUSSION

The intended impact model for the support (Figure 2) was used to create an evaluation plan. Then the evaluation was carried out leading to the results. The results are discussed in comparison to the intended impact on profitability to answer the second research question. The discussion starts with the three tiers within the actual impact model (Figure 6) and ends with the automation potential.

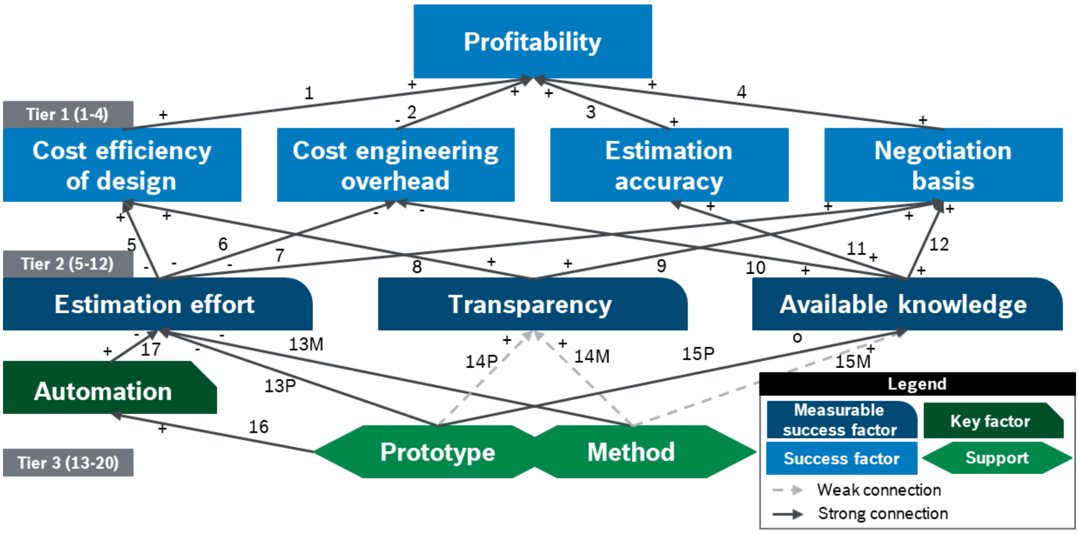

Figure 6. Actual impact model

First, the impact of the four identified success factors (cost efficiency of design, cost engineering overhead, estimation accuracy and negotiation basis) on profitability was researched within literature (Tier 1 in Figure 6):

All influences could be verified in literature or through direct observation in the research environment. According to Hintzen et al. (1989) profit optimization needs cost-efficient and technically mature designs (#1). As the cost engineer's workload is added to the products project costs, less calculation effort lowers the overhead and increases profitability (#2). Tracking production costs and selling prices structurally increases profitability. As targets are set and observed in a structured process, accurate cost estimations for the given functionality are essential (#3). A better understanding of product costs in negotiation can lead to savings in procurement. (Lysons and Farrington 2016) (#4).

Second, the impact of the three measurable success factors (estimation effort, transparency, available knowledge) on the success factors is discussed (Tier 2 in Figure 6):

When reducing the time needed for a cost estimation, the time until a design engineer becomes cost feedback decreases through more likely cost-efficient design changes. Additionally, faster development cycles can be realized. This can lead to more cost-efficient design (#5). Moreover, cost engineers can support more products at the same time, resulting in smaller cost engineering overhead of products (#6). The enabling effect of non-experts in cost engineering is seen to extend into purchasing and there gives a better negotiation basis, for example through the identification of an alternative process chain (#7).

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More transparent cost estimations enable a better insight, for example by management or purchasing. When cost drivers therefore are easier identified, they are more likely to be worked on and solved, which leads to more cost-efficient designs and in negotiation with suppliers, knowing cost drivers leads to a better negotiation basis (#8, #9). Correlations #10, #11 and #12 can be confirmed by high time saving with the partly automated prototype.

Third, the impact of the developed support (Method and Prototype) and the automation topic is discussed (Tier 3 in Figure 6). A strong indication within Figure 3 is interpreted as indicatively confirmed connection, while a weak indication is considered as unclear:

Both, the questionnaire and the interviews show a positive impact of the prototype and the method on the estimation effort (#14P and #14M). The prototype is also seen as implementation of the positive impact of automation (#16, #17). Nonetheless, the potential of the method depends on data availability. In the research environment, the enabler is the consequent use of a 3D-Master model with integrated product and manufacturing information.

Transparency is a success factor important for user acceptance. All participants had a similar understanding of transparency. There were participants seeing added transparency through the method and participants explicitly stating no transparency gain through the prototype. Therefore, the transparency gain for the method is seen likely, but could not be formally verified (#14M), while the prototypes influence continues to be unclear (#14P). A likely reason for the prototypes assessment is the development status with corresponding difficulties in user interaction.

One of the methods intentions is identifying fitting reference system elements, but the positive impact of the method on the available knowledge could not be confirmed (#15M). Otherwise, for the prototype the data indicates a positive impact (#15P). While this is positive news for the prototype implementation, it also shows the wide solution space for implementing the method.

The automation potential of the method steps can be classified in three clusters. Even though, the study explicitly asked for the potential of the method, a mix-up with the potential of the prototype by participants cannot be excluded. Steps S4 and S6 show the highest potential as the computer-aided calculation and the upload of the results into the knowledge graph seem easy to implement to the participants. This fits in the authors view, as those steps are mostly already automated within the prototype. The potential of steps S1, S2 and S3 was estimated medium due to the foreseen implementation work. Here, the prototype still has improvement potential and basic requirements such as the 3D master and a basic knowledge base, still need to be established on a bigger scope for adequate usage. The 5th step "Check results" still requires a manual check which corresponds with the low potential evaluation. Finally, the study shows different automation potential within different tasks and therefore the need for a targeted instead of a generalized approach.

6 SUMMARY AND OUTLOOK

This research indicates a positive effect of the developed support on profitability. The impact chain through reduced calculation effort was verified, while the impact on transparency and the knowledge base was only partly verified. Automation shows high potential on further reducing the manual effort, but as effort and benefit of different method steps differ widely a targeted approach should be followed. Overall, the benefit of the support is seen, but further improvements are needed.

Future support needs an improved transparency, a smart level of automation and the integration of manufacturability expert knowledge for user acceptance. The implementation strongly depends on prerequisites, such as the 3D-Master with product and manufacturing information availability and the knowledge base quality. As this data is often not available, further work on continuously available product and manufacturing data is needed. Product and production system complexity rises, resulting in a need for support not only on component but system level. Here, further research in the connection of product functions and manufacturing costs for example with advanced systems engineering methods is needed.

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