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Analysis of the requirements of an early life-cycle cost estimation tool: an industrial survey

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Abstract

Cost estimation is a critical issue for many companies concerning both offers generation and company strategic evaluations. In this paper, a framework for early cost estimation has been proposed to some firms for an assessment of its main features. The aim of the industrial survey is to promote a discussion on the needs and the expectations regarding cost estimation in order to obtain feedbacks to be addresses in the implementation of a software tool. Gather data has led to a ranking of the main characteristics the tool should have.

Keywords: Knowledge-based engineering ; Design to Cost ; Product configuration ; Early cost estimation ; CAD ; PLM

1. Introduction

The business model of many companies is based on the customization of the products in the portfolio. In particular, Engineer To Order (ETO) companies offer new products according to the customer technical requirements summarized in the request for proposal (RFP). The RFP contains the expected technical requirements

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and trigger a negotiation phase ending with the offer generation. Therefore, a simplified but complete design process is needed, and it involves time-consuming activities and technical expertise. A customer RFP often leads to a significant number of alternatives, so, it is important to identify the most significant requirements and the constraints in order to define a reliable offer. In the early design phase some activities require a priori choices, which leads to different alternatives depending on the chosen decision path. Moreover, the compliance to several constraints, e.g. weight and overall dimensions, will be checked only after some activities of the design process have been performed, leading to a rough configuration process and thus an inaccurate cost estimation.

Over the last 20 years, some methodologies have been defined to assess costs before product realization in order to optimize product and process design, such as Design for Manufacturing and Assembly (DFMA) approach [1], Feature-Based Costing (FBC) [2], Design to Cost (DTC) [3]. However, their application in industry is limited due to the required data analysis and complex knowledge structuring as well as numerous resources to be involved in the project. On the other hand, different approaches like knowledge-based engineering (KBE) [4], artificial intelligence (AI) algorithms [5], object-oriented (OO) design and functional programming [6] have been conceived to capture, structure and reuse design knowledge, possibly automating repetitive tasks and optimizations. Although the availability of such tools, it has been observed that many companies base the cost estimation process on poor empirical models working by analogy on the basis of the expertise of senior designers and searching for similar past solutions. Then, product BOM is adapted and costs are updated accordingly.

The most important problems encountered of such estimation methods are the following:

(1) The resulting cost is strongly affected by the subjectivity of the cost estimator;
(2) The elaboration of the technical proposal and the commercial offer is time consuming;
(3) Required expertise in a wide area;
(4) Difficulties in retrieving information of past cases;
(5) Difficulty of connecting information, e.g. customer specifications and BOM;
(6) Difficulty of making the most economic choices during the product configuration;
(7) Difficulty of taking into account the product life cycle, including RAMS analysis (see nomenclature) within the proposal.

The above cited problems lead to the need of a method and tools for early product configuration and cost estimation. Such tools should manage the company knowledge relative to the product life cycle, particularly the product design and manufacturing knowledge. Knowledge should be elicited and formalized, allowing the past cases retrieval and the relationship between customer specifications and the product configuration. Finally, the tool should allow a rapid definition of a new product configuration and its costs.

Based on such considerations, a research program has been started aiming at conceiving a platform to support stakeholders in the process of the early estimation in the view of the Life-Cycle Cost (LCC) of the new product. The paper investigates the requirements of such a tool on the basis of the literature background and the industrial needs. A structure of the system is depicted along with the main functionalities that should be provided.

Nomenclature

AI	Artificial Intelligence
BOM	Bill Of Material
CEF	Cost Estimation Formula
CSP	Constraint Satisfaction Problem
DFMA	Design For Manufacturing and Assembly
DSM	Design Structure Matrix
DTC	Design To Cost
ETO	Engineer To Order
FBC	Feature-Based Costing
IT	Information Technologies
KBE	Knowledge-Based Engineering
LCC	Life-Cycle Cost
OO	Object-Oriented

PLM	Product Life-cycle Management
RAMS	Reliability, Availability, Maintainability, and Safety
RFP	Request For Proposal
SME	Small and Medium Enterprises

2. State of the art

2.1. Early cost estimation

Duverlie and Castelain in [7] have identified four different methods of cost estimation: (a) the intuitive method, (b) the analogical method, (c) the parametric method and (d) the analytical method. The first is based on the experience of the estimator, leading to the problem (1) above discussed. Although (d) is the most accurate method for cost estimation, it requires much time, i.e. problem (2), and a lot of information from embodiment phase, becoming not applicable at the early design stage or during the offer generation. (b) and (c) remain the most feasible methods for cost estimation in the offer stage. A comparison between (b) and (c), has led to the conclusion that these methods can be combined using a case based reasoning system to search for similar cases and then adapting the selected case with Cost Estimation Formulas (CEFs) on the basis of similar extracted cases. In this context, the cost estimation tool should work with a database of past cases, allowing data retrieval and similarity measurement, such as the Minkowski formula [8]. In order to comply with the problem (7), the CEF should take into account the LCC, that is a financial estimate intended to help buyers and owners determine the direct and indirect costs of a product or system extended to the use and end-of-life phases, going beyond the initial manufacturing costs.

2.2. Product configuration

As discussed above, in order to make a reliable offer, a configuration of the required product is needed. As often requested by the customers, offers shall include the technical proposal compilation, with the proposed solution and the main product data, the list of the most significant components, and, in many cases, preliminary drawings including product overall dimensions. Therefore, product configuration consists in finding the set of components and their arrangement, which fulfil the customer requirements.

Sabin and Weigel [9] describe configuration as a special case of design activity with two key features: the component types involved in the configuration process belong to a fixed set and the component interact in predefined ways. The constraint-based approach is probably today the most used way of dealing with configuration problems, in which components and their ports are the variables and the constraints restrict the solutions space. The goal of such a problem is to find at least one product architecture satisfying all the constraints. CSP can be solved by dedicated solvers (e.g. Geocode [10], a free tool). Given an objective function, optimization algorithms allow to find the best solution among possible (e.g. cost minimization).

In order to model the problem as a CSP, knowledge regarding the product life-cycle needs to be formalized. Chandrasegaran et al. [11] provide an extensive overview of knowledge representation in product design systems. Raffaeli et al. [12] show a step-by-step method to acquire and formalize the design and manufacturing knowledge of a company in a systematic manner. The method involves the use of IDEF0 for representing the activities and parameters network and the use of the DSM to sequence the design activities. The authors point out that the approach is suitable for products with a good level of standardization and/or modularization.

3. Approach

This paper introduces and analyze the requirements of a software platform to support the cost estimation of new products at early design stages. The framework is proposed to guide the user in the requirements definition, identifying conflicts and solving dependencies between them. Furthermore, the user is supported during the configuration steps in assigning attributes to blocks and dependencies between blocks. The cost estimation is derived as a consequence of the choices made at each configuration step. The framework has been conceived to manage both the product structure and its 3D representation. The first is mainly used to manage the product hierarchy, attributes, relationships, and immaterial modules (e.g. software); the second allows managing product geometrical constraints and overall dimensions. The two product views are connected each other, which means that information flows in both directions. For instance, the user assigns relationships between two parts (e.g. axis alignment) by using the 3D view and dependencies between part attributes (e.g. axis speed and torque transmission) by using the product structure view.

In order to face the problems identified above, hereunder the list of relevant features prioritized using the MoSCoW method [13]:

(1) The tool *Must* be integrated with other company software and data repositories
(2) Knowledge formalization *Must* be supported
(3) Integration with CAD tool *Must* be provided
(4) AI support in finding one or more valid solution *Should* be included
(5) The cost estimation *Could* to be based on a parametric approach

The following paragraphs detail such features.

3.1. Integration issues

The proposed system is to be integrated with consolidated systems within the company trying not to overlap already covered functionalities:

- CAD, which provides a geometric environment for the embodiment design phase;
- CAE, which provides an environment containing simulation tools for design validation and optimization;
- PLM, which provides product classification and product life-cycle management;
- ERP, which provides an integrated environment for the management of the core business process

Moreover, the integration must be extended to a large variety of customized company tools, such as performance models or simulation software. The system shall work with a large variety of data coming from different tools. For instance, several companies make use of spreadsheets for component dimensioning and evaluating several possible scenarios.

Integration will be implemented by using API library which are commonly provided by commercial tools. Thus, the proposed framework has been thought as a part of an integrated environment, which links product knowledge coming from design, manufacturing, marketing, maintenance gathered from the company departments: technical, production, service, commercial and purchasing departments. Managed knowledge extends to the product life cycle, enhancing standardized interfaces to acquire information.

3.2. Company knowledge formalization: a model-based approach

The company knowledge is embedded in a model-based architecture, which is able to describe the families representing the company business.

Product families are described by modules arranged in a hierarchical manner, each one providing a functional task of the product. Functional description and modules can be identified thanks to modularization methods [14]. A component-oriented approach, limited to the most significant parts, is proposed in order to describe the most relevant blocks of a product. Each introduced part is connected to its functional description. In this context, the scientific literature review provides a broad overview of approaches and methodologies to obtain structured functional representation of a product, with the aim to offer a wider range of variants and models to meet the consumers' needs [15].

Therefore, in the proposed framework the product model is described in terms of blocks and dependencies. The block is a basic part which has relevance to the designer in the conceptual phase and is described by a set of attributes. The block, initially defined in abstract terms, becomes a real part code when attributes have been completely defined. Blocks interact each other by means of dependencies, which are relations or constraints between attributes. Dependencies can connect two or more blocks, forming in general a hypergraph.

A set of predefined blocks and dependencies constitute the starting database for product configuration and cost estimation. In fact, cost is computed from the attributes of the blocks. A block is retrieved from past project for fostering reuse of existing solutions. The storage of the defined parts forms a DB that continually grows. The system, thanks to a recommender system, supports the user in finding and selecting codified parts from the DB, with the advantage of reducing the codes number and moving towards parts standardization.

Traversing functions are introduced as a mean for computing cumulative quantities provided by homogeneous attributes that belong to sub sets of blocks. The subset are identifiable in the product structure as branches of the blocks hierarchy itself, or thanks to dependencies connecting parts from a logical point of view (e.g. parts connected by a hydraulic circuit).

Finally, product requirements play a pivotal role in product configuration and in cost estimation. The product cost itself can be regarded as a product requirement, which is a constraint to be respected in the product configuration. A block containing the product requirements is linked to the product architecture.

3.3. Integration of CAD environment

Because of the importance of product geometry during the configuration step in many industrial fields, the blocks, if applicable, contain geometrical descriptions to generate simplified 3D models. CAD models must respect overall dimensions and interfaces for blocks connections, even if simplified representations. The configuration of a simplified layout provides the relevant information for a product geometry assessment. This information can flow from the 3D layout to the product attributes in order to verify constraints or calculate some quantities, e.g. the painting costs by means of the rough external surface of a geometry. Parametric template CAD models are linked by the system. Such templates are interactively defined by the user to the necessary level of detail. The tool drives commercial CAD systems by API connections and allows updating geometries as parameters are changed, while its 3D environment is just limited to visualization functionalities.

3.4. Support towards a solution

The framework has been thought to continuously check for constraint satisfaction during product configuration in order to support the user in a flexible but consistent configuration. This is particularly suitable for managing the common case in which completely automated configuration processes are not feasible. In such a way, the user is guided towards a valid solution being free to navigate the design space. As long as the configuration problem can be modelled as a CSP, a solver powered by an optimization tool can be employed to find valid and optimal solutions.

3.5. Cost estimation issue

Since the aim of the framework is to perform an early cost estimation, a parametric method is the most suitable for this purpose, allowing a rapid evaluation that follows the configuration process. In fact, since a block is described by a set of attributes, the cost of each block can be expressed as a function of its attributes (such as weight, length, area, etc…). In practical terms, product cost estimation follows two main paths distinguishing purchased materials from produced parts. The proposed cost estimation method for purchased parts is based on regression models, which can be derived by fitting the costs of past purchased codes using one or more relevant parameters (e.g. the power of an electric motor and the output torque for a gear box). Cost estimation for produced parts are deducted by more complex cost models based on cost centres, allowing a better management of the company resources involved in the manufacturing and life cycle processes. Because of the costs are attributes of the product, depending on blocks attributes and relationships, they are stored for a possible future reuse. Product or part similarity measurements allow a better costs estimation by retrieving the past cases. Adaptation formulas are then used to cover the differences between attributes of different parts, allowing a more accurate cost estimation than the stand-alone parametric CEF.

4. Results

4.1. Company interviews

The framework delineated above has been presented to a set of companies in order to promote a discussion on the company actual needs, the potential of the depicted system in their environments, and by encouraging advices for improving the framework. In particular, the system has been introduced to 9 companies, designing and manufacturing products of different categories, ranging from automotive (test benches, motors) to highly customized machines (machining centers, agriculture machines, defense systems, cranes). The involved companies span from SME to large enterprises. In order to demonstrates the designed features, a demo of the framework has been presented during a series of three workshops, each one lasted about two hours, in which people from the company departments (e.g. IT, cost engineering, mechanical engineering, purchasing) and the authors worked together to apply the framework concepts to selected products.

Although there are some differences in the needs, it has been found that all the companies expressed the necessity of estimating the product cost at an early design stage. In many cases, it is required when preparing an offer for customized products as an RFP containing the product requirements comes from a possible customer, while in others it is important to perform a rapid cost evaluation for placing new products on the market. In the latter cases, the target cost achievement is often required, meaning that the cost become a product constraint.

Table 1 summarizes the most relevant aspects emerged from the workshops.

Table 1. Main aspects emerged from the workshops with the companies

Company	Products	Needs	Suggested integration	Comments and advices
Loccioni IT manager	Highly customized test benches	Offer generation for customized products	Product hierarchy must be derived from PLM.	The tool is useful for offer stage, not in the design stage because of the difficulty in making parametric and reusable technical solutions.
Biesse Cost Engineering	Machining centers (mainly for wood)	Offer generation for product variants	PLM can be used to extract the list of the functional modules of the machine.	Development costs (engineering, test, quality) and the effect of batch quantities must be included in cost estimation.
Fip industriale Mechanical Engineering	Anti-seismic devices	An analytical cost estimation is required	-	A software for analytical cost estimation is already implemented. Given the standardization of the product, additional tools are not desirable.
Maschio Gaspardo CAD/PLM manager	Agriculture machinery - medium batch	Early cost estimation for product variants	A commercial configurator must manage the new product variants.	The company perceives the system more useful for customized products than small or large series.
GE Power Cost manager	Turbogas power plants	Early cost estimation for new power plants	An integration with performance evaluation tools is required.	The company needs parametric cost models at different detail levels depending on few parameters, modules and main parts list.
Leonardo Cost Engineering	Defense systems	Cost estimation for new products	Cost estimation shall be integrated with the CAD environment.	Parametric cost estimation shall not be limited to the company knowledge base. The tool must contain a cost driver repository.
Fosber Purchasing manager	Paper-making machinery	Target cost achievement	-	Parametric cost models must also consider the machine technology and the market field, supporting a target cost reasoning.
Fiat Power Train Cost manager	Industrial diesel motors	Cost estimation of new or customized products	-	The framework appears more useful in the customization of an existing product rather than in new products design.
Meloni T.H. Commercial manager	Material handling machines	Offer generation for customized products	The tool must be integrated with spreadsheets used for parts dimensioning	A CAD generation of the machine layout for the customer assessment allows time saves in the offer stage.

Table 2 shows a synthetic view on the appreciation of the platform features by the interviewed companies. The score 2 has been assigned if a company has shown a big interest in the feature, 1 for a medium interest and 0 for no interest. Firstly, the interviews have confirmed the hypothesis that the current cost estimation approach mostly follows analogic methods based on product similarity. Moreover, cost estimators mainly work on product BOM, adapting previous projects according to the new product requirements.

People involved in the workshops have showed that the framework is consistent with the actual companies' needs. The interviews have showed the importance of integrating this framework with the systems currently used by the company, which are mainly CAD, PLM, ERP, configurators and spreadsheets. In some cases, companies use customized tools, e.g. for the product performance evaluation, which must be integrated with this framework. Companies have underlined that the tool must not overlap with the current tools and must not replicate information, because the data redundancy could lead to errors and cause waste of time.

The discussion concerning the perceived needs has led to several suggestions, resulting in features to be possibly included in the development stage. The needs of a rapid cost estimation combined with the lack of accurate information at the early design stage, require the parametric cost models to be defined at different level of details, i.e. general and approximated at the first stages and more precise as the design process progresses.

Table 2. Ranking of the software features

Feature	Loccioni	Biesse	FIP ind.le	Maschio Gaspardo	GE Power	Leonardo	Fosber	FPT	Meloni TH	∑ (feature appreciation)
Knowledge storage	2	2	2	1	2	2	1	2	1	**15**
Knowledge formalization	1	2	2	1	2	2	1	1	2	**14**
TCO	1	2	0	1	2	1	2	1	1	**11**
Product requirements	2	2	0	1	1	0	1	2	2	**11**
Parametric cost	1	1	0	0	2	2	2	1	2	**11**
Product structure	1	1	1	2	2	1	0	0	2	**10**
Detail level	1	2	0	1	2	1	1	1	1	**10**
Support to solution	0	1	0	1	2	1	2	1	2	**10**
Target cost	0	1	2	2	1	0	2	2	0	**10**
Integration	2	1	0	1	2	1	0	0	2	**9**
Cost repository	0	1	1	1	0	2	2	1	0	**8**
CAD tool	0	0	1	1	0	2	1	1	2	**8**
∑ (global appreciation)	**11**	**16**	**9**	**13**	**18**	**15**	**15**	**13**	**17**	**-**

It has been observed that cost estimation cannot be only based on internal company knowledge, because it would limit the design choices, as in the case of the use of new manufacturing technologies. A cost driver repository, which contains shared manufacturing cost models and design solutions would allow to explore new technical solutions and perform a wider cost estimation. A power plants manufacturer has underlined the importance of a LCC estimation, dividing the product cost (CAPEX), which is the investment, from the running cost (OPEX), which depends on plant performance. Furthermore, it has been noticed that the customer often requires a model of the product layout attached to the technical proposal in order to verify the product geometry and constraints (e.g. the capability of the hook of a crane to cover the whole working environment), thanks to preliminary CAD model generation. The debate has also showed the importance of considering the product from the perspective of functional modules, which are able to carry a functional description and allows an easier knowledge formalization.

From the discussion, the authors concluded that the framework needs to be adapted and extended in order to meet the following three features:

(a) inclusion of cost drivers that go beyond the current company knowledge base;
(b) supporting of target cost reasoning;
(c) cost estimation should be carried out at different level of details.

In particular, the third point highlights the need of managing several cost models at different detail levels following the project stages: from a pure parameter-based model for a rapid cost estimation when few information is available, to a modules-based model for a more accurate medium-detail cost level, to an analytic model working in the final BOM for a precise cost estimation of the parts to be produced. In fact, as the level of details become finer, the level of uncertainty decreases and the costs become more accurate.

Finally, from Table 2 is evident that companies manufacturing customized products are the most interested in the presented framework, because it satisfies their needs of early cost estimation and offer generation for new products. Moreover, since the framework is suitable for modular products, companies used to reason with product families and functional modules, have showed a higher interest.

5. Conclusions

The results of the interviews summarized in Table 2 reveal the most important features to be included in the framework. Although the companies have appreciated the majority of the proposed features, the knowledge storage and formalization are those with the highest scores. Both of them contribute to the building process of a company knowledge base, which is essential for cost estimation. Parametric cost estimation has been recognized as useful since it leads to a rapid cost estimation at the early design stage, also considering the LCC. Product requirements management has been found to be very important, mainly in ETO companies, which need a product functional description for comparing product functional characteristics and making cost evaluation during the offer stage. In this paper, the companies' interviews have confirmed the need of a tool for early cost estimation, which can support both the phase of offer and the economic evaluation for placing a new product in the market. In conclusion, the delineated framework could meet the requirements of the majority of the companies for early cost estimation, mainly for those producing customized products based on customer requirements.

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