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Design to cost; a framework for large industrial products

Iban Retolaza[a,]*, Iñigo Ezpeleta[b], Adrian Santos[a], Iban Diaz[a], Felix Martinez[a]

[a]Ikerlan Technology Research Centre, Basque Research and Technology Alliance (BRTA), Pº J.M. Arizmendiarrieta 2, Arrasate/Mondragón 20500, Spain
[b]Mondragon Unibertsitatea, Faculty of Engineering, Mechanical and Industrial Production, Loramendi 4, Arrasate/Mondragon 20500, Spain

* Corresponding author. Tel.: +34-943712400; fax: +34-943796944. *E-mail address:* iretolaza@ikerlan.es

Abstract

One of the main aspects that must be considered while developing any industrial project is its cost. Design to Cost (DtC) processes allow the design team to manage any kind of project based on the costs of each of the phases and of the elements, by applying a number of methodologies, techniques, cost models and tools. In this paper, a DtC framework is proposed, taking other DtC centered research as references and focusing on a probabilistic approach, in order to lead the early design stages of large industrial products, where most of the information is unclear or is still being defined. A literature review about DtC methodologies and techniques is first carried out in order to analyze, compare and classify them and identify the strengths and weaknesses of each one.

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Keywords: Design to Cost; Cost estimation; Cost model; DfX; Cost management

1. Introduction

In recent years, and even more so on entering this century, the complexity and quality of products has increased. In fact, new technologies are even more advanced as time passes by and, therefore, they become obsolete or outdated even faster. Indeed, the global technology market can be seen as a race where companies must constantly fight to maintain the lead or, at least, to keep a competitive pace in an increasingly demanding market. In order to achieve this objective, it is imperative to be able to create opportunities and to make the most of them. However, some obstacles must be overcome in the process, such as uncertainties and lack of information [1].

Knowing how to implement all the innovations that are developed is not enough. Obtaining the required resources implies a significant amount of financial support, and the only way companies can achieve that support is by guaranteeing profits. That is why predicting costs and developing cost management methods has become one of the most important factors in industry, and that's how Design to Cost [2] has gained in popularity. These predictions should ensure as much accuracy as possible. Underestimating could result in increased costs later on, and overestimating could lead to certain projects not being approved. That is why there are several tools and methods to help avoid these potential problems.

Most of the research on this topic agree that there are two main approaches for cost estimation: probabilistic and deterministic [3,4,5]. The first one is applied when the information is not completely clear, at early stages of a project [6,7,8], while the second one is more useful for later computations, with more complete information [8]. This paper will focus on developing a probabilistic approach, as this is designed to be applied at the early design stages of large industrial product-related projects, where most of the information is unclear or is still being defined. Indeed, the early design stages do not require great financial resources, but most of the total project cost is actually defined in these phases (close to 70-80% of the total cost) [9].

2. Literature review: DtC methodologies and techniques

Predicting costs allows companies to speed up decision making processes, cost administration and the creation of a

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budget for a specific project. Good estimations have a direct and important impact on companies' effectiveness. That is the reason why time and resources have been invested to study and develop new techniques and methodologies aimed at optimizing this kind of processes.

This paper shows a review of several topics attached to DtC, such as cost estimation methodologies, cost models and a brief review of optimization related studies.

2.1. DtC methodologies

Lots of methodologies have been studied and proposed over the last decades in order to obtain accurate cost estimations for projects. For example, Hari et al. [10] propose a "Conceptual Design to Cost" (CDtC) approach that combines the main characteristics of DtC method with the Pareto principle (also known as the "80-20 rule" or "vital few, many trivial principle"). It is divided into six phases: Target Cost definition, Cost Model definition, Cost Drivers definition, Assembly/Test concept graphic development, Evaluation of the cost attached to each cost driver, and Analysis and Validation of the results [10].

Collares Pereira [11] proposes a combined methodology that takes elements from a Design for Manufacturing (DfM) approach and Concurrent Engineering (CE). It is a sequential, cyclical methodology that tries to reach "Good Enough" solutions for a specific problem.

Another methodology that has been analyzed is the one proposed by Ercoyuncua et al. [12], based on the existing uncertainties during the early phases of a project. Known as U-TASC (Uncertainty Tool for Assessment and Simulation of Costs), this process has four phases or steps: the first step consists of detecting uncertainties and classifying them; next, the cost drivers are defined and linked with the previously identified uncertainties; then, the estimations are made by an Analytical Hierarchical Process (AHP); lastly, the Monte Carlo method, which is usually applied in cost modelling [13,14], is applied to obtain the best, worst and most probable case scenarios.

There are also Knowledge Based Systems (KBS), Artificial Intelligence (AI) led programs that gather, represent and process information and data (knowledge) in order to generate new knowledge areas. They also can substitute for an expert, as they can "make decisions" based on the knowledge obtained [15,16]. In the Architecture, Engineering and Construction (AEC) industry, KBS have been developed and applied for various purposes, such as cost estimation [17]. However, Aram et al. [18] assure us in their research that these systems only work efficiently in ideal scenarios, and that they cannot perform well if there is a lack of data.

Vaidya et al. [19] links the concept of energy efficiency with the primary costs of a project. The proposed methodology is a variation of the "Whole Systems Integrated Design Process" [20] where the following steps are specified: Find optimization opportunities for constructing system interdependence and synthesis; cost optimization (especially the primary ones), and redundancy elimination by methodical analysis. This methodology presents several Bundling options for cost analysis and optimization [19]. Although it is completely aimed at high performance building design, the methodology can be applied in other industrial sectors.

Furthermore, Sequeira and Lopes [21] propose a simple methodology based on the combination of Work Breakdown Structures (WBS) and a Responsibility Assignment Matrix (RAM) and the latter's variations.

2.2. Mathematical models for cost estimation

Apart from the methodologies, cost estimation models have also been examined in this research. They have been classified into three groups: Component level models, General level models and Maintenance cost estimation models.

2.2.1. Component level models

One of the main parts of the designing process of a product is the definition of how its components will be manufactured and the costs of each element within it (materials, operations, finishing, etc.) and, consequently, the cost of the overall process.

For example, Molcho et al. [22] present two different approaches, CFD (Costing for Designers) and CFM (Costing for Manufacturers). Both are similar computation models, but there are a few factors that are changed, depending on who is making the prediction and their preferences.

Niazi et al. [23] presents a cost estimation model review and, among those models, a couple of them stand out. One of them is an operation-based estimation model that is usually applied at late design stages due to the required information (instead of calculating the value of an individual product or part cost, it focuses on the batch). Niazi et al. [23] also mentions a Cost Breakdown approach, where more factors are taken into account (maintenance, repairs, insurance, etc.).

In another research, Niazi et al. [3] proposes an overhead cost estimation model. It consists of multiplying the overall costs (except direct material and labor costs) by the MLT (Manufacturing Lead Time) estimated for a new product.

There are also several models for specific manufacturing processes, such as welding [24], melting [25] or composites [26].

2.2.2. General level models

Three general level models have been identified (there are others, but they are mainly variations of these ones). These models can be applied for any case, project or project phase.

One of them is ABC (Activity Based Costing), and it is one of the most used models due to its simplicity. It consists of identifying the activities required for a specific process, hierarchically classifying them, selecting the cost drivers, establishing a correlation, and estimating the costs [27,28].

Another model is the parametric estimation, based on lineal regression analysis, which is calculated based on the relationship between a series of data (parameters) and the consequently obtained linear function [29].

The third one is analogy-based costing. Its main characteristic is that it is fully based on historic information and fully completed projects that are "like the "current" one". This model allows different levels of complexity to be set, from basic comparisons and mean value computation, to more complex predictions obtained by a number of equations and algorithms [30].

2.2.3. Maintenance costs

The "maintenance" concept can be defined as "the combination of all the technical actions (and the administrative ones related to them), including their supervision, in order to keep or restore the correct functioning of a system" [31]. Two types of maintenance are identified: preventive/predictive and corrective.

There are several approaches and research work related to this topic. The University Fermín Toro [32] explains an easy way to calculate the possible maintenance costs, based on the costs of every factor, element and consumable involved in the process. Renovetec [33] have their own maintenance managing manual and cost optimization is one of its chapters. They show a simple cost estimation equation based on part replacement/correction costs.

Other models are similar to the previous ones, but they take into account additional factors, such as depreciation [34]. Edwards et al. [35] propose an equation that allows a calculation to be made to ascertain the increase in the cost of the maintenance based on the economic inflation ratio.

Seo and Ahn [36] present one of the most complete, simple and fastest models, based on labor cost, time and the labor time/cost ratio, the replacement cost and the frequency of the failures.

2.3. Cost optimization

Even if the DtC process mainly consists of cost estimation for decision making, it is important to mention some cost optimization and reduction methods. This topic can be analyzed from different perspectives, for example, with the main factors being either the production and element distribution [37,38] or the tooling and the set up [39,40].

Other researchers [41] analyze the performance of a product and its costs based on tolerance quality, or they try to improve the whole life cycle cost [42,43].

Some other research examines the cost reduction topic focusing on general aspects [44] on repetitive activity sequence-based projects [45] or optimizing costs by improving the correlation between invested time and cost [46,47].

One of the most studied aspects is the industrial system maintenance cost optimization. Indeed, Dekker [48] identifies up to 112 related research and case studies. Other investigations focus on improving the maintenance operations [48,49,50,51,52] and others study several ways of reducing costs, applying algorithms and mathematical computations [53,54].

3. Proposed framework

After completing the literature review about DtC, a framework is proposed. Frankly speaking, in general terms, all the previously identified methodologies can be independently applied to such projects. Nevertheless, on the one hand, the proposed framework tends to better suit the design of large industrial products and on the other hand it can take advantage of combining the best of each of them.

Table 1. Pros and contras of each analyzed methodology.

Methodology	Application	Pros	Contras
CDtC	Project early stages	- Not much information needed for estimation	- Component-level knowledge required
DfM-CE	Design phase	- Constant control of client willingness to pay	- Better if done by a team
Uncertainty-based	Design phase with lack of data	- Methodical and organized	- Can become a long process in big, complex projects/products
KBS	Any sector and phase	- Easy to understand and apply	- Optimization-centered, not estimation
High-performance building-aimed method	Building design phases (Suitable for other sectors)	- Constant iteration and validation	- Requires Target Cost
Component manufacture-leaded method	Design phase	- Several solutions for a single problem	- Requires specific tools
WBS-based	Project early stages	- Constant cost optimization	- Requires historic information

As can be seen, there is no "perfect" methodology. All of them have their advantages and disadvantages; for example, KBS-based methodologies depend directly on AI-based systems, which are really useful and accurate but they are not always available (as they tend to be an expensive resource). On the other hand, methodologies such as the "High-performance building-aimed method" [19] or the "Component manufacture-led method" [17] offer accurate results and proper cost optimization strategies. However, they require detailed information about the product, which is not usually available in the early project stages (where the proposed methodology will be applied); and the "Uncertainty-based methodology" [12] can be quite complex while being applied, which could result in a time increase (and, as a result, cost increase). The "WBS-based methodology" [21] is really simple and easy to understand (indeed, not many resources are needed) but it is closely linked to the ABC cost model, which makes the application of other models difficult. "CDtC" and "DfM-CE" approaches are sequential, cyclical processes that guarantee a constant control over the project evolution. Although some product or component-level information is required, this is not as critical a factor as it can be in other methodologies, as a high level of detail is not strictly necessary. Moreover, these methodologies do not depend on specific tools (software, cost model…) and appear to be quite compatible. Looking at all the main characteristics, of each methodology, the conclusion is that instead of choosing a single one, the best option is to take the best attributes of each one and combine them to propose a new methodology.

Table 2 shows the main structure of CDtC and DfM-CE methodologies, which will be the basis for the proposed framework. The framework will not depend on specific tools (although they could be applied, if there is an opportunity) and all the analysis will be based on the conceptual alternatives that the design team propose. This way, the proposed methodology will be clear and simple enough to allow any team to manage their project, independent of the resources they have.

Table 2. CDtC and DfM-CE methodologies summary.

CDtC	DfM-CE
-Determine Target Cost -Define cost model -Identify cost drivers/factors -Assembly/Test graphics for project control -Cost evaluation for each cost driver -Result analysis and validation	-Set different solutions for the product -Concurrent Engineering for each proposed solution -DfM process for each proposal -Select, classify and validate the most suitable options

The proposed framework will consist of three main phases: Target Cost Definition, Design Solution Proposal and Cost Definition, and Result Analysis and Validation. The framework diagram is shown in Fig. 1.

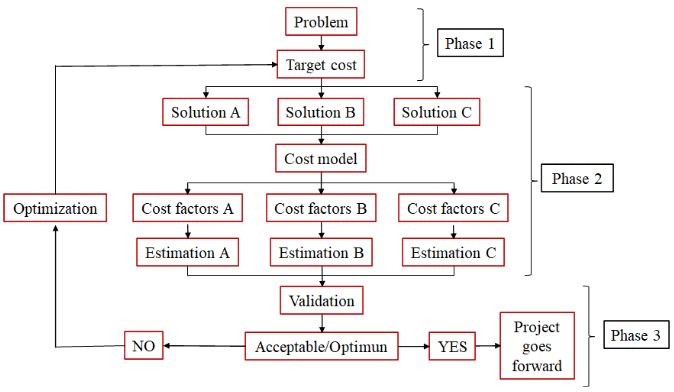

Fig. 1. Proposed framework scheme.

3.1. Phase 1: Target Cost Definition

The first step will be contacting the client and establishing the cost they are willing to commit to. The client will determine which features and attributes will be included within the product/project. Three levels will be identified: "Basic" (essential attributes, minimum possible cost), in this category two levels can be established, standard and customized; the "Medium" level includes non-vital but beneficial attributes that improve product performance; and the "High" level aims for more luxurious features that add value to the product.

This phase will require several market and product analyses in order to identify as many references as possible and fix a realistic Target Cost.

3.2. Phase 2: Design Solutions Proposal and Cost Definition

To solve the identified problems or requirements, the design team propose different design solutions that will be implemented in the upcoming product. These solutions will be analyzed concurrently, applying CE processes. Consequently, the team will have a global view of the full project evolution and the proposed solutions/alternatives.

From each design solution, every cost related attribute will be identified (materials, parts, installation processes, maintenance, etc.); in other words, all the cost drivers/factors will be defined.

Each driver/factor will have a specific impact on the overall cost of the proposed solution. The objective of this phase is to identify those values (make an estimation) in each proposal in order to later make a further analysis of them. Before this, a common cost model must be established for the calculations, selecting the most suitable mathematical model and tools, in accordance with the client's preferences and available resources.

For large product design, the models that are best suited are the "General Level" models (ABC, Parametric estimation, Analogy-based estimation). ABC is useful while analyzing sequential processes such as mass part production or component assembly and product installation processes (usually based on linear correlation between cost and a specific factor, time for example). The other ones are useful when this linear correlation cannot be established (when costs vary according to several independent factors, such as part volume, mass or material), or when the processes involved do not follow sequential schemes.

The next step will be to compute and collect all the estimated costs in a database to later start the analysis and validation process.

3.3. Phase 3: Result Analysis and Validation

This is the most important step in the process (it will define the path the project will take) and it is the most likely to vary depending on the situation and the previously obtained results. Once the cost estimation results have been obtained, the design team decides whether the values fit the defined objectives. Five classification levels are proposed:

- Not valid: Does not fit the objectives and cannot be improved
- Potentially valid: Does not fit the objectives but can be improved
- Valid/acceptable: Fits the objectives, but cannot be improved
- Potentially optimum: Fits the objectives and can be improved
- Optimum: Best possible option, surpasses the fixed objectives

For cost optimization, any of the approaches mentioned in the literature review could be used (depending on the aspects or attributes that could be improved). The most useful or versatile ones could be the general aspect-centered approaches [44] or the time/cost correlation-centered ones [46,47], as time is one of the most important resource when developing an industrial project.

After setting the classification, the improvable options will be optimized, and three levels will remain: "Not Acceptable", "Acceptable" and "Optimum".

The ideal situation is to take the Optimum level solutions or the Acceptable ones; but sometimes this is not possible, so three alternatives have been proposed: rework the solutions, accept the Not Valid options, or rework the objectives.

4. Conclusions and future work

DtC is a broad process that can include lots of concepts - as many as the project team decides. It can vary depending on the project specifications or the client's requirements.

Indeed, from the literature review, it can be concluded that, with regard to the general scheme of the different methodologies, there is no specific format for different kinds of projects to design large industrial products that need to install in the field. Instead, most of them have similar structures, they have sequential, even cyclical, processes that allow the team to adapt them to whatever the particular project is aimed at. Most efficient cost models are the "General level" ones (ABC, parametric and analogical). On the one hand ABC is more useful for sequential process-based projects, where the activities or operations can be easily identified (such as part production, installation processes…). On the other hand, parametric and analogical estimation models are useful when lots of historical information is available and the cost relationships are not lineal, or when the operation sequences are not available or they are difficult to identify.

The conclusion is that instead of choosing a single one, the best option is to take the best attributes of each one and combine them. Moreover, it is more efficient to use general scheme-based methodologies and later combine them with cost estimation tools, rather than applying specific tool/technique-based methods.

Based on these conclusions, a new DtC framework has been proposed. This framework is suitable for large mechatronic, industrial product design that needs to install in the field. This framework will consist of a 3-phase sequential and cyclical process, based on the combination of the CDtC and DfM-CE methods. The main objective of the proposed approach is to manage the overall costs during the design process for these kinds of products, by proposing several solutions and analyzing their cost impact based on a specific classification method, and then, the most suitable ones will be selected. The structure of the framework allows the team to check the project status regardless of the stage or phase that is being developed. Applicability was also one of the criteria used and followed while developing the framework. The approach does not depend on specific systems, software or tools to perform well, so it can be applied easily. However, it does not mean that such tools cannot be used to improve certain stages. To sum up, the framework has been proposed in order to allow the team to constantly and correctly manage large industrial product-based project costs with the minimum resources.

For the future, a proper case study should be carried out, in order to prove the validity of the proposed framework (it is currently only a theoretical approach). This research could even be combined with other DfX (Design for Excellence) approaches, such as DfMA (Design for Manufacturing and Assembly), DfM (Design for Maintenance) or DfI (Design for Installation). Apart from this, the cost optimization research should be amplified, given that the information provided in this paper is only a brief review of the most relevant research.

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