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Human-Driven Design-to-Cost Methodology for Industrial Cost Optimization

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Abstract. Over the years cost optimization has gained a strategic importance to realize competitive products. However, traditional approaches are no longer efficient in modern highly competitive industrial scenarios, where numerous factors have to be contemporarily considered and optimized. In order to be effective, design has to care about cost along all its phases. This paper presents a methodology that integrates Design-To-Cost (DTC), Design for Manufacturing and Assembly (DFMA), Human Factors (HF) and Feature-Based Costing (FBC) to include costs from the early conceptual design stages and properly drive the product design. Thanks to a structured knowledge base and a FBC approach, it predicts both manufacturing and assembly processes from the 3D geometrical models and estimate the global costs, more accurately than existing tools. The research demonstrates the method validity by an industrial case study focusing on cost optimization of packaging machines. Thanks to the proposed method, the main design inefficiencies are easily identified from the early design stages and optimization actions are taken in advanced, in respect to traditional design process. Such actions allowed reducing total industrial costs of 20%, improving machine assemblability and human ergonomics due to structure simplification, part number reduction, and production processes modification, and reducing the time spent for cost estimation (until -60%).

Keywords. Cost modeling, Cost optimization, Design-to-Cost (DTC), Feature-Based Costing (FBC), Knowledge-Based engineering (KBE).

Introduction

Nowadays, product and system design must contemporarily deal with and optimize numerous factors such as performance, aesthetics, time-to-market, sustainability, quality and cost [1]. Traditionally, a product cost target is defined at the beginning of the design process and verified at the end: whereas it is not respected, design is iteratively changed in order to find a compromise between performance and cost objectives by minor incremental improvements and long optimization loops. In this context, cost seems a performance indicator rather than a real design driver. Several studies demonstrated that a large percentage (at least 70% up to 80%) of product cost is already determined during the conceptual design phase and, once the product concept is defined, there is no much room for significant changes since total cost are almost already defined by product architecture, assembly procedure, quantity of components

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and their related manufacturing process. As a consequence, the majority of the costs are already frozen with product conceptualization and costs for the following product modification grow exponentially along the development process stages [2, 3].

Today several methods and tools are available to assist product managers in decision-making to evaluate the cost of alternative design solutions [4]: for instance, Design for Manufacturing and Assembly (DFMA) allows assessing the product cost by analyzing the production processes when the product is designed in details, while Group Technology (GT) and Computer-Aided Process Planning (CAPP) can manage the knowledge connected to cost definition. However, such tools have three main drawbacks:

1. they are usually “static” tools suitable for validation and verification;
2. they require a lot of information to provide a clear cost structure, so that they can hardly used from the preliminary design stages; and
3. they do not consider the human-related aspects so that human-based activities are difficult to model and predict.

As a consequence, their use is complex and time-consuming, and usually limited to advanced validation phases [4]. Furthermore, human-related activities are usually neglected from the process cost estimation because they can be hardly standardized and have been considered not important for final cost definition. Contrarily, it has been recently demonstrated that human-related actions highly affect the global efficiency and costs of industrial processes in different contexts of application, from material handling to assembly, from order picking to operations in line [5, 6]. At the present moment, the most common tool adopted by companies all over the world for early cost estimation and optimization is represented by excel worksheets supporting the experience of very skilled people able to make the right assumptions. However, such an approach is highly timewasting and subjective, and not fully reliable due to the necessary approximation and the possibility of human errors.

According to these evidences, the present paper proposes a Design-To-Cost (DTC) approach to estimate the product cost from the earliest design stages, which combines Design for Manufacturing (DFM) to model industrial processes and create a structured process knowledge base, Design for Assembly (DFA) to model the human-related actions and create a structured human knowledge base, and Human Factors (HF) to assess the human efforts and identify its efforts and related costs. Furthermore, it adopts Feature-Based Costing (FBC) principles to fasten the analysis by recovering the 3D geometrical features and link them to the related processes, both machining and human-driven, to predict the final costs. The main paper contribution consists of the adoption of human activity assessment for the definition of more accurate cost models.

1. Related works

The DTC approach aims to support cost-efficient product design by defining a clear target cost at the beginning of the design activity, to be respected along the process by properly managing the knowledge related to the production process [7]. According to DTC approach, cost analyses are fallen back to the early design stage so that the conceptual models continually interact with cost considerations. DTC is easy in its concept, but hard to implement in practice due to the complexity of the products and systems designed, and the complexity and variety of the production processes to be estimated and refined along the design process. Furthermore, the close relationships between performances, geometries, manufacturing process, aesthetics, and costs and the reciprocal effects of such factors make cost estimation a critical job in the conceptual stages. Moreover, costs are highly variable according to market demands, production volume, cost amortization, and other logistics costs. In order to be successful, DTC needs to be based on solid cost estimation models able to estimate the production costs according to consistent assumptions, when specific data are not available.

Among them, the Design for Assembly and Manufacturing (DFMA) theory was defined to assess efforts and costs related to fabrication and assembly processes [8]. In particular, DFA aims at reducing the number of components providing a list of criteria through which the effective need of each part can be evaluated, and DFM allows the manufacturing process optimization and provides elements of cost for each component (e.g. raw materials, set-up costs, processing costs, additional costs) [9]. Such estimation could be by manual procedures or dedicated software toolkits. A good review of the existing cost estimation methods has been recently provided by [10]: they can be distinguished in quantitative and qualitative. Qualitative estimating techniques, also called intuitive, rely on experience and knowledge of product cost estimators, being cheap and fast in implementation. Differently, quantitative estimating techniques use mathematical algorithms and statistical tools, and set the value of product cost with respect to the manufacturing process specifications [11]. More recently, the FBC approach proposed to identify the product features as geometric information and collect all functional and technological information (e.g. tolerances, surface finishing, manufacturing cycle, etc.) and to use knowledge-based systems to apply the most proper cost models [12, 13]. FBC seemed very promising approach since it allows anticipating the analysis from the early design stages, fastening the estimation process, and supporting the costing process by a software tool. However, the cost models proposed in literature are mainly focused on manufacturing processes, where machines operate and humans are considered as an additional costs of the machines, without considering whether and how Human Factors (HF) affect such cost models.

In this context, human activities have been recently analyzed and modeled mainly for ergonomic purposes, more than for cost models' definition. For instance, Maudgalya et al. [14] and Hendrick [15] investigated the effects of bad workplace ergonomics on productivity, quality of production, safety and costs, while Falck and Rosenqvist [16] assessed the cost of bad ergonomic performances for specific manual operations. Another interesting study defined an ontology that integrates human's knowledge and experience with product features and computational capabilities [17], but it focused on design parameters analysis rather than a real cost estimation. However, such studies demonstrated the importance of HF on the global process costs and suggested that also human-related aspects should be included into cost models to have a reliable cost estimation and effectively adopt a DTC approach.

2. The research approach

2.1. The Human-driven Design-To-Cost approach

The DTC research approach is based on the quantitative estimation of product-related costs and, in particular, exploits a FBC analytic methodology. The approach can be summarized into four main steps, as shown in Figure 1. The main phases are as follows.

1. *Process knowledge formalization*: the first step focuses on the formalization of both engineering process knowledge and human-related process knowledge, in order to define cost models with different levels of detail. In both cases, the knowledge base is structured by identifying a set of different process classes and dividing each class into categories. For instance, the production technologies are divided into classes (e.g. chip-forming machining, injection molding, stamping, die-casting, painting, thermal treatments, superficial covering, etc.), and each class into categories (e.g. machining class has been subdivided in milling, turning, grinding, gear cutting, broaching, slotting, etc.). Each category is further characterized by a set of typical operations, which define the specific cost model by mathematical formulas. Similarly, human-related processes are divided into classes (e.g. manual assembly, assembly with devices, handling, moving parts, etc.) and each class into categories (e.g. manual assembly class has been subdivided according to the part typology like pipes, rings, etc.). Therefore the operations are univocally mapped with a specific set of geometric and non-geometric elements defined as a set of features, to obtain a set of cost models. Each model combines the geometrical product parameters characterizing the specific operation (e.g. length, width, depth, roughness, etc.) with process characteristics (e.g. type of machine, machine power, number of operators required, human actions required, etc.). As far as engineering processes, the knowledge has been structured as suggested by [9, 13]. The same approach has been extended to cover also human-related processes, which are usually missing. In this way, the product design model (bi-dimensional or tri-dimensional) can be represented as a collection of process features. The knowledge formalization defines three main cost models: simplified, feature-based (FB) and detailed. The difference mainly lies in the number of parameters considered and the complexity of the mathematical models described. Usually this activity is carried out by people belonging to cost engineering department and with the involvement of the more strategic suppliers.

2. *Design concept optimization*: the second step consists of a preliminary optimization of the product design concept, expressed by a bi-dimensional or a tri-dimensional model, by the application of DFM and DFA techniques, but exploiting the wider knowledge base. At this stage, simplified cost models about both processes and human tasks are used to analyze the product structure and the main assembly sequences, inferred from the product structure by standardize models, as well as materials adopted and main technological processes. Such a step allows product simplification and optimization according to the process characteristics and estimated cost. At the end, an optimized 3D conceptual product model is defined. Usually this activity is carried out by designers.

3. *Feature-based cost estimation*: the third step starts from the decomposition of the 3D conceptual product model in its elementary geometrical features, and the correlation between its features and the manufacturing and assembly process stages, according to the FB cost models. Such models express the association between geometric product features and technological process features, that can be achieved only by a proper feature recognition algorithms and process knowledge formalization, in Step 1. During this step, the design features can be optimized according to a cost-oriented design; human tasks can be validated in time, security and costs; and different production scenarios can be simulated. Such analysis can be easily integrated within CAD tools and embedded into early design processes, in order to simplify and fasten the estimation process. This activity is basically carried out by designers, with the support of suppliers and partners in co-designing.

4. *Cost-oriented detailed design*: during the last step, product and process design is developed in details with adoption of detailed cost models, that take into account both process operations and human activities. At this stage, cost estimation of both product and process is very detailed, thanks to accurate models (considering also set-up costs, tooling, logistics, etc.) and is usually carried out in a parallel way. This activity is usually carried out by cost engineering and production technologists. According to the proposed methodology, this step can benefits from previous cost-oriented design actions and design is optimized easily and in a more effective way, in respect with traditional methods. A reduced number of design changes are required at this stage.

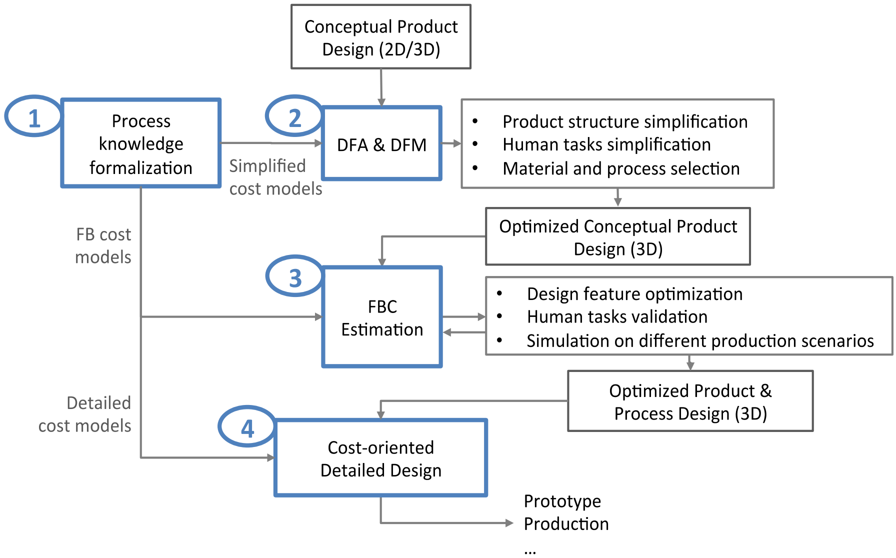

Figure 1. Human-driven DTC approach for industrial cost optimization.

2.2. The process cost modeling

This section describes in more details cost modeling and knowledge formalization, as mentioned in section 2.1. In particular, for almost any manufacturing process, costs are assessed by considering different types of times and hourly machine and plant cost. Three types of times are defined:

- *Active Time* (T_{ON}): time period when the machine / plant is running;
- *Accessory Time* (T_A): time spent for preparing to work a specific part even if the machine doesn't effectively work the part (e.g. time for machine changing tool or piece);
- *Set-up Time* (T_S): time spent for setting up the machine before starting working a lot production (e.g. CNC program testing, tool setting up);
- *Idle Time* (T_{OFF}): time period when the plant is idle;

For each of this time period, an hourly cost for each machine or plant is defined; the cost model is represented by a set of equations that combines the geometrical and technological parameters involved in the specific process. In particular, for each component manufacturing cost is composed by four cost items:

- *Operation cost* (C_O): cost for machining a part, calculated multiplying the time while the machine works the part by the machine unitary cost;

- *Stock cost* (C_S): cost for stock material, obtained multiplying the weight of the stock required by its unitary cost;
- *Ancillary cost* (C_A): cost related to accessory time, calculated multiplying the corresponding time by the machine unitary cost;
- *Machine set-up cost* (C_{MS}): cost related to the set-up time, obtained multiplying the corresponding time by the machine unitary cost.

An example about face milling is proposed. Table 1 describes the characterizing geometrical and technological parameters and the formulas. The cost estimation of face milling operation (C_{OP}) is calculated by the following equation (1):

$$C_{OP} = \left[\left(\frac{L+E}{VAs} * NPs * NWs\right) + \left(\frac{L+E}{VAf} * NPf * NWf\right)\right] * C_M \qquad (1)$$

where C_M is the machine hourly cost, calculated on the basis of company data. Using the same approach, every automated manufacturing, assembly, logistic and management operation is described by a specific cost model.

Table 1. Example of feature-based costing process estimation (e.g. face milling).

Type	Parameter	Description (unit of measurement)	Relations
Geometrical	*L*	*Length [mm]*	*from 3D model*
	Lsp	*Shouldering length [mm]*	*from 3D model*
	P	*Depth [mm]*	*from 3D model*
	W	*Width [mm]*	*from 3D model*
	Ra	*Roughness [µm]*	*from 3D model or specifications*
Technological	*E*	*Over travel [mm]*	*= CONST*
	VAs	*Feed speed in rough machining [mm/min]*	*= f (material, machine)*
	VAf	*Feed speed in fine machining [mm/min]*	*= f (material, machine)*
	K	*De-burring width (W) in percentage [%]*	*= f (material, machine)*
	NPs	*Number of rough machining passes in depth [no.]*	*= CONST*
	PPs	*Rough machining pass depth [mm]*	*= CONST*
	PPsp	*Shoulder pass depth [mm]*	*= CONST*
	Ke	*Number of fine machining passes in depth [no.]*	*= CONST*
	NPf	*Number of fine machining passes in depth [no.]*	*= CONST*
	WI	*Width limit [mm]*	*= CONST*
	NWs	*Number of rough machining passes in width [no.]*	*= CONST*
	NWf	*Number of fine machining passes in width [no.]*	*= CONST*
	Df	*Milling cutter diameter [mm]*	*= from DB*

2.3. The human-oriented cost modeling

This section describes in more details human-related cost modeling and knowledge formalization, as mentioned in section 2.1. In particular, the activities carried out by humans are analyzed and divided according to their typology, and the related cost is assessed by considering the manpower hourly cost for the execution and additional costs related to the level of risk connected with the activities, that can cause injuries to workers according to ergonomic guidelines. Related costs are calculated according to the feature-based modeling and the proper knowledge base, and consequently the related costs are calculated. In particular, according to the DFA principles, human activities are classified into *handling* and *insertion*. The main product features considered are:

- *Thickness* (T): thickness of the handled item or part;
- *Size* (S): maximum dimensions of the handled item or part;
- *Weight* (W): weight of the handled item or part;
- *Orientation* (α): angle of insertion of the item or part;
- *Operation* (Op): type of operation executed (i.e. bending, riveting, screwing, fastening, soldering, adding material, etc.);
- *Level of difficulty* (L): level of difficulty of the specific operation (i.e. low, medium, and high). It is defined according to ergonomic principles, in particular Rapid Entire Body Assessment (REBA) and Rapid Upper Limb Analysis (RULA) [18], on the basis of historical company data.

Furthermore, the following parameters are considered:

- *Labor hourly cost* (C_{HR}): hourly cost for workers involved;
- *Handing time* (T_H): time necessary for executing handling operations;
- *Insertion time* (T_I): time necessary for executing insertion operations;

Labor cost is defined according to the company rates, while standard values for T_H and T_I are defined for each specific type of operation by a set of logics based on experimental data. Operations are classified according to a specific set of the above-mentioned features. In some cases, a range of value is considered (e.g. for thickness, size, weight, orientation) according to the specific industrial sector. Table 2 shows the parameters considered for manual assembly, divided into geometrical and functional. Figure 2 shows an example of logics to assess the handing time (T_H).

Table 2. Example of feature-based human costing estimation (e.g. manual assembly)

Type	Parameter	Description (unit of measurement)	Relations
Geometrical	*T*	*Thickness [mm]*	*from 3D model*
	S	*Size (dimensions)[mm]*	*from 3D model*
	W	*Weight [kg]*	*from 3D model*
	α	*Orientation [deg]*	*from 3D model or specifications*
Functional	*L*	*Level of difficulty [no.]*	*= [1:10]*
	Op	*Type of operation*	*= f (process, T, S, W, α) from DB*
	T	*Tool supporting the operation*	*= f (process, T, S, W, α) from DB*
	H	*Handling condition*	*= f (process, T, S, W, α) from DB E.g. one hand, aided-one hand, two hands.*
	I	*Insertion condition*	*= f (process, T, S, W, α) from DB E.g. secured (or not), separated (or not).*
	A	*Access condition*	*= f (process, T, S, W, α) from DB E.g. easy, medium difficult, highly difficult.*

Handling ID	Category	Type	Tool	Param_0	Param_0_values	Param_1	Param_1_value	Line_value
one_hand	manipulation	assembly	hand	alpha	0;90;180	beta	0;90;180	0
one_hand	manipulation	assembly	hand	alpha	0;90;180;360	beta	0;90;180;360	1
one_hand	manipulation	assembly	hand	alpha	180;360	beta	180;360	2
one_hand	manipulation	assembly	hand	alpha	360	beta	360	3
aided_one_hand	manipulation	assembly	grasping tool	alpha	<=180	beta	>=0;<=180	4
aided_one_hand	manipulation	assembly	grasping tool	alpha	<=180	beta	360	5
aided_one_hand	manipulation	assembly	grasping tool	alpha	360	beta	>=0;<=180	6
aided_one_hand	manipulation	assembly	grasping tool	alpha	360	beta	360	7
two_hands	manipulation	assembly	hand					8
two_hands_large	manipulation	assembly	hand					9

Figure 2. Example of logics for handling time estimation.

3. The industrial case study

3.1. The case study description and objectives

The industrial case study focuses on the adoption of the proposed methodology to improve the design of complex groups of automatic machines in the packaging sector, with the final aim to reduce global costs and production times, as well as to improve the human safety and ergonomics during their production. Indeed, on the basis of experimental testing, we found that shorter and easier tasks can be accomplished in less time, but also with a lower effort and easier actions, with a consequence minor risk of physical and cognitive workload. In particular, the case study focuses on filling machines, where a flat web of packaging material is properly modeled in order to create a closed package. The packaging material is introduced by pushing a male die into a female channel and creates a delamination inside the packaging material layer fibers. A crucial group in filling machines is the co-called "forming ring", which is realized in different sizes and mounted at different stages, through which the packaging material is modeled until the final shape. The forming ring requires high-quality processes in manufacturing and assembly, especially for food sector where the whole system have to be aseptic and all components have to respect severe tolerances and roughness values. Figure 3 shows the product 2D drawing and the 3D model. Such product has been re-design in order to reduce cost and improve the productivity.

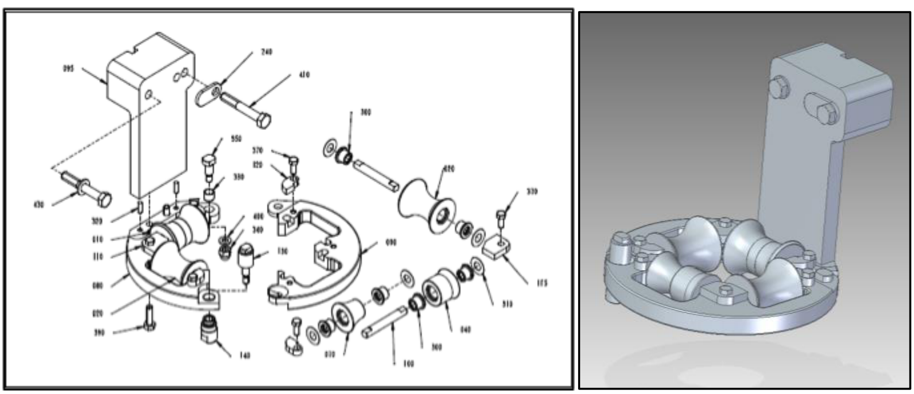

Figure 3. The case study product (i.e. forming ring).

In on-going production such product showed some criticalities, which the study aims to solve, in particular:

- High cost in respect to the total machine;
- Long time for cost estimation and optimization, for specific custom applications;
- Long assembly time;
- High number of components to be assembled;
- Low percentage of component reuse;
- Handling and insertion difficulties.

3.2. Results and discussion

During the case study the forming ring has been analyzed and re-designed according to the proposed methodology. First of all, the company knowledge related to the specific product was analyzed and formalized into a set of databases as described in section 2.1. About the human-related aspects, the sequence of operation were inferred from the production cycle and assessed in terms of times and level of risk. Indeed, the most common human postures during operations were mapped into a database and associate with a standard time and a standard value of RULA and REBA scores, according to ergonomic principles. After that, the manufacturing and assembly processes were analyzed and optimized. Cost estimation and optimization was faster and easier in respect to previous method thanks to the adopted FBC approach and the automatic identification of some features directly for the 3D model.

Results are shown in Table 3, where the main savings calculated on the optimized design in respect with the original design. Savings are distinguished in four categories: design, human factors, technological, and business. The first important benefit is the great reduction of the cost estimation time (-60%) that is achieved thanks to the automatic feature recognition from the 3D model according to the FBC approach. In this way, numerous simulations can be carried out easier and faster. Furthermore, the DFMA approach allowed reducing the number of components and interfaces (respectively -20% and -24%), while the human-driven approach allowed improving the quality of manual operations with a great reduction of handling and insertion difficulties (respectively -38% and -32%) and ergonomic risk (expressed by RULA and REBA) thanks to the reduction of fasteners and the easier assembly sequence. Such results brought to both technological benefits in terms of manufacturing and assembly times (respectively -16% and -37%), with a consequent impact of global industrial cost saving (-20%) and profit (+8%). The new design solution cannot be shown due to non-disclosure agreements.

Table 3. Saving obtained with the optimized product

Category	Indicator (unit of measurement)	Savings* (% on average)
Design	Time for cost estimation (min.)	- 60%
	Number of components (No.)	- 20%
	Number of interfaces (No.)	-24%
	Component reuse (No.)	+15%
Human Factors	Handling difficulties (No.)	-38%
	Insertion difficulties (No.)	-32%
	RULA	-20%
	REBA	-35%
Technological	Manufacturing time (min.)	-16%
	Assembly time (min.)	-37%
Business	Industrial cost (euro)	-20%
	Profit (euro)	+8%

* *in respect to original design*

4. Conclusions

The paper presents a methodology to support industrial cost optimization of complex systems by the identification of the most critical issues in product structure and manufacturing and assembly process operations, considering both machining and manual operations. The main contribution of the paper is the enhancement of traditional Feature-Based Costing by human-driven approach, based on the optimization of ergonomics and Human Factors. An industrial case study taken from the packaging sector demonstrated the validity of the proposed methodology and the great achievable benefits. Thanks to the proposed method, the main design inefficiencies can be easily identified from the early design stages and focused optimization actions can be taken in advance. Result showed how the improvements of handling and insertion operations can bring great benefits on process time and cost, improve machine assemblability due to structure simplification, part number reduction, and production processes modification, and reduce time spent for cost estimation.

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