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Cost Estimation Method for Gas Turbine in Conceptual Design Phase

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Abstract

Introduction of new gas turbine machines on market is a complex project that requires optimization of different performance parameters such as power, efficiency, maintenance plan, product cost and life. The ability to control cost and impact on performances and life strongly decreases from conceptual to detailed design phase.
Actually, 80 % of product's cost and performances are committed based on decisions made in conceptual design.
This Paper describes a systematic procedure to estimate the cost of multiple design alternatives during conceptual design phase, comparing different cross sections for gas turbine solutions.
Examples of parametric costing tool for part family will be described, to show the approach that allows to estimate costs in conceptual design phase, when detailed design has not been developed and lack of information is a daily topic.
The idea is to be able to read design information of each part from an enhanced cross section and enter parametric costing tool to have a preliminary cost estimation in conceptual phase.
Doing that for each part or module present, it will be possible to estimate total cost of the product.
The scope is to create an internal database where the whole know-how and best practices are stored. This database can be examined in early program stages, to reduce time to market and avoid pursuing solutions that would not be viable or convenient, in a sort of digital twin approach.
Another positive aspect pursued and presented, is the positive impact on engineering productivity, that directly reflects on program development cost.

Keywords: new product introduction, gas turbine, target cost, conceptual costing, parametric cost estimation

1. Introduction and State of Art

New Product Introduction is quite a complex procedure while dealing with gas turbine product.

A lot of performance targets shall be met, from power to efficiency, from manufacturability to maintenance. Each single choice is a trade-off study between different scenarios, to select optimized solution for a specific application. Cost as well can be considered an internal target to match, and its related business case for a specific NPI project.

As explained in [1] and [2], about 80 % of cost is locked-in at conceptual design stage, when project teams freeze the cross section of the new machine even though the knowledge gap is higher, up to 60 % [3]. Proceeding in design development, cost of change increases as stated in [4].

Should cost at conceptual design is slow and unreliable due to a lack of a specific tool, and this limits the evaluation of design alternatives. Development and validation of a configuration at conceptual stage requires months, limiting the exploration of design alternatives.

Time constraints prevent effective cost optimization in conceptual design phase, as stated in [5] and [6], since no automation is available for cost versus performance checks. Value estimation is used to be a qualitative procedure based on intuition of an expert or on analogies of similar products, as described by Niazi [7].

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Ability to reduce cost decreases while cost accuracy increases with ongoing time in design process as described in Figure 1.

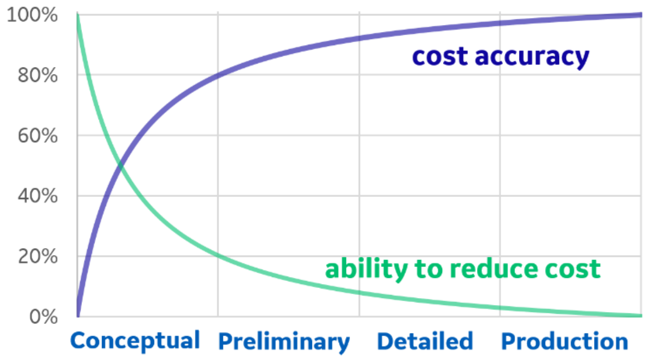

Fig. 1. Impact on Cost Vs. NPI program stage -

The paper objective is to describe a systematic approach to compare different design options and predict cost implications through parametric cost models developed internally.

The idea is to leverage parts cost drivers to generate quick cost assessments for each item [8] and [9]. By doing that for each item of the bill of material, and adding the assembly procedures cost contribution, it is possible to evaluate total product cost. Xu et all, in [10], cover several key areas in Cost Engineering, from design to manufacturing cost, from operating to life cycle cost (LCC) and risk costs. Gu et all, in [11], deal with implicit costs and quality cost efficiency, giving a wider overview to product total cost using analytic method. On the contrary, Cicconi et all, in [12], present a parametric approach to cost estimation during embodiment design phase.

The novelty of this paper is related to the specific field of interest (gas turbines). No literature cost models where available, due to the high complexity of the product, but also to the fact that cost models cannot leave aside the supply chain used to manufacture all the components, relying both on external suppliers and on internal capabilities, and pushing to optimize balance between cost and lead time.

This is for sure the first goal achieved, while a depth internal knowledge on cost assessment is under construction inside design engineering teams.

This article will deal with the method of parametric estimation, describing how it is related with the parametric simplified model with preliminary attributes and how it fits specific product structures, in a feature-based approach as described in [13].

A case of study will be presented: Axial Compressor' Disks cost models for both forging and machining procedures will be deeply analyzed, describing which are the main contributions to the cost achieved and how we can predict value of a new design.

Manufacturing and assembly procedure are properly evaluated to understand if some criticalities will lead to cost increase [14].

Results on this specific case of study will be discussed and extended to other items to complete the parametric cost mapping of all the possible items. The aim is to be able to evaluate at least all the scale and mix of scenarios already produced in factory.

Nomenclature

BOM	Bill of Material
GT	Gas Turbine
LCC	Life Cycle Cost
NPI	New Product Introduction
PBS	Product Breakdown Structure
PMI	Product and manufacturing information
PO	Placed orders
SC	Should Cost
TDT	Total Drilling Time
TGT	Total Grinding Time

2. Materials and Methods

2.1. Parametric Cost Estimation for GTs

The aim is to leverage GT parts cost drivers to generate quick cost assessments, doing that in an accurate but also quick way during conceptual or preliminary in design, when lack of information is inherent to the stage of the project.

At Step 1 a sketch, so called Cartoon, is generated: Cartoon is a preliminary enhanced cross section, enriched of information and used in this stage to compare different conceptual solutions.

Cartoon generation is related to product structure, from a Cartoon it is possible to generate a PBS (step 2), as described also in [15] and [16], and vice versa when a PBS is selected it is possible to create a Cartoon of the gas turbine.

The Cartoon is created by a software tool called Cartoon Generator and it will be composed of simplified model with preliminary attributes and features: attributes and PMIs necessary to provide information for Cost Estimation. Cartoon Models are completely parametric and associative. Step 3 is related to simplify model with preliminary attributes regarding geometry and PMIs for cost estimation.

From step 3 it is possible to enter parametric cost estimation at step 4 for each item included into PBS.

Parametric cost estimation will provide components cost using configured gas turbine database as input. See fig.2 to understand flow information.

This procedure allows to estimate the costs of multiple design alternatives during conceptual design phase, comparing different Cartoon cross sections for gas turbine solutions.

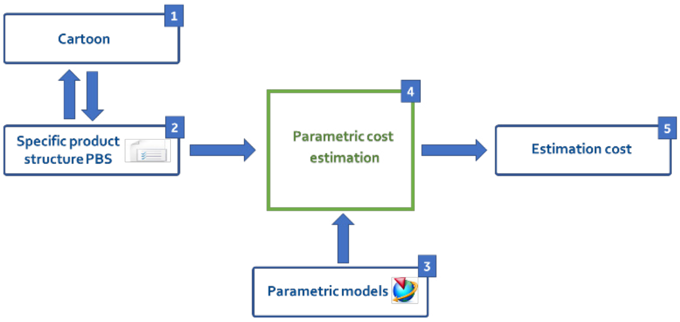

Fig. 2. Parametric Cost Estimation Structure - © 2019 Baker Hughes, a GE company, LLC - All rights reserved.

2.2. Parametric Cost Models Development

The idea is to be able to read design information of each part from an enhanced cross section and enter parametric costing tool to have a preliminary cost estimation in conceptual phase. Doing that for each part or module present, it will be possible to estimate total cost of product. Assembly cost shall be considered as well to correctly estimate total product cost.

Input are read by CAD or automatically imported from geometrical features or manual input at the very beginning of the project and elaborated through parametric cost curves to estimate part value.

The flow chart of the following steps is described in fig.3.

In step 1, all the orders of items belonging to a same family group are collected together. To populate structure and database of parametric cost estimation first of all it is necessary to collect data from historical PO.

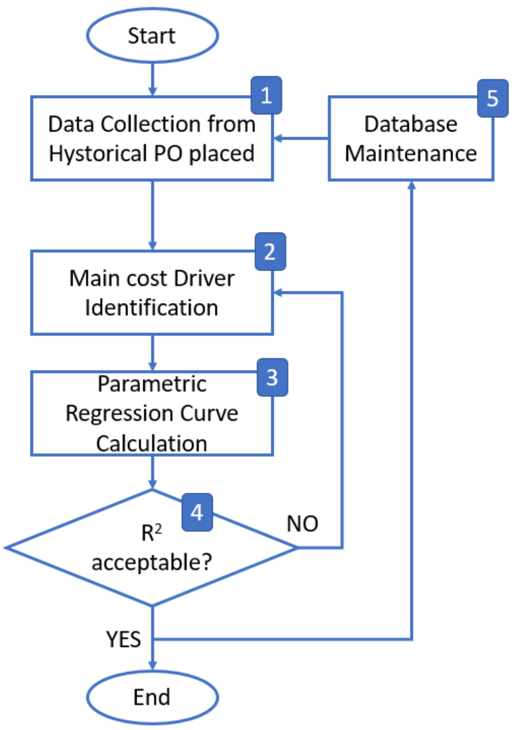

Fig. 3. Parametric Regression Curves Flow Chart - © 2019 Baker Hughes, a GE company, LLC - All rights reserved.

Step 2 is the first attempt to generate a cost model: a preliminary supposition of main cost drivers is made based on experience and previous cost models realized and then to find correlation and identify cost drivers (step 2). Some items and parts, even if not properly of the same family type, have been considered together because of material type communality and machining cycles similarities.

As a first attempt, screening and data analysis looks for proportionality between cost and simple parameter such as weight and preliminary parametric cost regression curves are calculated in Step 3. In Step 4 R^2 is calculated as described in [17] and in case regression fit data points within acceptable accuracy the process is completed.

For R^2 higher that 0.9 a satisfying correlation is already met. R^2 values between 0.6 and 0.9 suggest proceeding with a deeper analysis of data, to identify more cost drivers. R^2 values lower than 0.6 are not acceptable and no correlation can be used for further studies.

Step 5 deals with database maintenance over years. Curves shall be updated during time to take into account new data points introduction while new orders have been placed.

Sometimes more complex cost drivers shall be considered and a deeper drill down analysis is needed, causing an iteration loop. Statistical analysis can be needed to identify outliers and refine cost models. Only when a good correlation is reached, the parametric cost model can be considered viable to be included into parametric costing tool.

An important aspect is related to supply chain identification, in fact a major difference in terms of supply chain is between full buy item, purchased by external suppliers, and make components, for which internal capability is used.

Each individual machining phase of a cycle have been described in terms of the following base operations and evaluated through a specific parametric equation.

Typical base operations are drilling, turning, milling, grinding, painting, balancing and assembly.

For each machining or operation type, set up hours as well as machining time and cost related to inspections, pack and shipment shall be considered and properly estimated.

Cost parametric function can be queried in an automatic way or, while the tool development is still in progress, to maximize and anticipate benefits of the tool itself, even with a manual approach, using a manual input interface.

Parametric costing tool and equations for a specific part family (disks) will be described in the next paragraph to show the approach that allows to estimate costs in conceptual design phase, when detailed design has not been developed yet and lack of information is a daily topic.

3. Case Study

Rotor disks total cost can be estimated by two main contributions. Raw material cost is the cost of the forged part, supplied by external partners (farm-out). On the contrary, rough and finish machining of disks is manufactured with a farm-in approach. Raw material parametric curves have been calculated by dividing POs into clusters, depending on material of disk. That means that the very first cost driver is the material selected. Afterwards, for forged parts is it possible to find a very good correlation between part weight and item cost. Many curves have been defined, one for each material available in our database selection, and entering the proper material curve, with the expected part weight, it is possible to have a raw material cost estimation.

In figure 4, parametric costing curves are shown for three different materials A, B and C.

As shown by R^2 values, some time is it possible to find a good correlation, some other correlation is lower.

A lower correlation can have different root causes.

One of that is the presence of outlier points (due for example to higher cost payed in case of urgency in procurement or lower cost payed in case of bundle buy volumes). In case an outlier point is identified it will be removed from the data point group.

Another possible explanation is the presence of other important cost drivers not addressed yet. In that case a deep dive into cost model generation and definition is needed to guarantee more accurate prediction. Only in case of real business urgency also costing curves with lower fitting can be used, adding a proper contingency value to consider variability of the prediction.

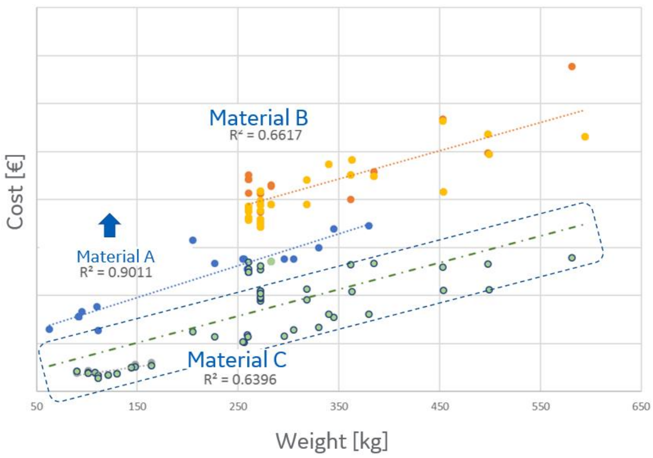

Fig. 4. Disks Raw Material Cost Vs. Weight -

For what concern machining cost, a first attempt has been made trying to correlate cost with delta weight between forged design and machined one of the same component.

The result is a leak correlation among numbers which lead to a deep dive analysis, looking for a better prediction.

First we defined the minimum set of geometrical parameters needed to describe item geometry of the machined part as mentioned in Table 1.

Table 1. Minimum set of geometrical parameters for disks -

Parameter	Units	Parameter	Units
External Diameter	[mm]	Groove quantity	[#]
Thickness	[mm]	Groove ext diameter	[mm]
Internal bore present	yes=1/no=0	Groove int diameter	[mm]
Internal bore diameter	[mm]	Groove depth	[mm]
Number of tire rod	[#]	Number of blades	[#]
Tie rod bore diameter	[mm]	Width of blades base	[mm]
Overstock material	[mm]	Depth of blades base	[mm]
Groove features	yes=1/no=0	Grinding surface height	[mm]

Parametric equations for two based operation are described below: drilling and grinding.

For drilling and grinding phases we have the following inputs:

Table 2. Drilling Phase Technological and Geometrical Inputs -

Technological Input	Description	Unit
$t_{drilling}$	Drilling time	[s]
$t_{reversal}$	Reversal time	[s]
$t_{load/unload}$	Load/Unload time	[s]
$N_{reversal}$	Number of reversal	[#]
$N_{load/unload}$	Number of load/unload	[#]
t_{setup}	Set up time	[s]
$t_{Online\ inspection}$	Online inspection	[s] = 0.16
$t_{Operator\ physiological}$	Operator physiological time	[s] = 0.05
T	Thickness	[mm]
d_{bore}	Bore diameter	[mm]
l_{bore}	Bore length	[mm]
h	height of grinding surface	[mm]
O	Overstock	[mm]

Parametric cost equation for drilling contribution is the following:

$$t_{drilling} = a + b \cdot l_{bore} + c \cdot d_{bore} \quad (1)$$

Where a, b, and c are constant calculated from regression, Drilling Time is measured in seconds and bore length and diameter in mm. Bore length is calculated as follows:

$$l_{bore} = T + O \quad (2)$$

Total Drilling Time TDT is then calculated as follows:

$$\begin{aligned} TDT = [(&t_{reversal} \cdot N_{Reversal}) \\ &+ (t_{load/unload} \cdot N_{load/unload}) \\ &+ t_{drilling}] + k[\, t_{load/unload} \\ &\cdot N_{reversal} + (l_{bore} \cdot N_{load/unload}) \\ &\cdot t_{drilling}] + t_{setup} \end{aligned} \quad (3)$$

Wherby:

$$k = t_{Online\ inspection} + t_{Operator\ physiological} \quad (4)$$

For the entire grinding time of the component, the equation is as follows:

$$TGT = [(\mathrm{t_{reversal}} \cdot \mathrm{N_{Reversal}}) + (\mathrm{t_{load/unload}} \cdot \mathrm{N_{load/unload}}) + (a \cdot h + b)] + 0.05\,[(\mathrm{t_{reversal}} \cdot \mathrm{N_{Reversal}}) + (\mathrm{t_{load/unload}} \cdot \mathrm{N_{load/unload}}) + (c \cdot h + d) + 0.16\,(e \cdot h + f) + t_{setup} \quad (5)$$

Where a, b, c, d, e and f are constants calculated through regressions, as described in [16] and relative mean absolute error and root mean squared error are calculated with the aim to predict accuracy of interpolation made using these equations.

The database we are building contains BHGE proprietary information data and cannot be shared in its completed form, but method described is general and example given for disk part family is representative of the approach followed.

Drilling and Grinding are only two factors of the whole parametric equation for disk machining. Each feature shall be realized on a specific machine and with a specific cost associated and time needed to perform the operation, and the scope of all these parametric equation is to describe as more accurate as possible the machining cycle to predict total lead time and cost. For the disk case of study, the gap between total cost estimated with parametric method and with analytic ones is always lower than 3 %.

4. Results and Discussion

As described in previous paragraphs, the scope is to create an internal database where the whole know-how and best practices are stored. This database will be examined in early program stages, to reduce time to market and avoid pursuing solutions that would not be viable or convenient.

Total product cost is obtained considering the cost estimated for each item or operation from the bill of material, and this means that a specific cost model for assembly operation shall be finalized as well.

As already stated, cost assessment is very important since early project stages, where the impact on total product cost can be maximized. On the other and, a trade-off between cost estimation availability and accuracy shall be met. In fact, at the very beginning of the project not all the information is available, and some assumptions are needed. Not all the cost contributions have the same accuracy: in fact, for example, machining cost are easy to estimate, leveraging experience of internal manufacturing capabilities. All the outsourced scope of work, i.e. forged parts or some specific coatings, will have a higher uncertainty in cost estimation.

A mitigation of this aspect is obtained engaging suppliers since the early stage of the program. The idea is both to have an accurate cost estimation, but also leverage their experience and know-how and implement positive feedbacks from their experience. Co-design approach with suppliers will help to meet the target as well as to predict cost in early stages in an accurate way. Another positive aspect pursued with all this effort is the positive impact on engineering productivity, that directly reflects on program development cost.

5. Conclusions

The major aim is to compare multiple design options and predict cost implications through design tools and cost model integration into each design phase, since early stages.

This example on axial compressor rotor shows that the approach is a strategic milestone even if a drawback consists in parametric cost equation maintenance effort. Actually, database shall always be updated considering new PO placed and scouting of new suppliers.

A further development in cost prediction and optimization can be reached through co design with suppliers, automated tools linked to the CAD system and for sure enlarging items database adding all the possible families for each applicable size in production with the scope is to create an internal database where the whole know-how and best practices are stored.

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