Gas turbine cost and value management in the conceptual design stage

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Abstract

The development of product concept is a crucial task which cannot leave aside value assessment and product cost management. Value engineering is in charge of ensuring that key operations are performed at the lowest possible cost while still meeting performance, reliability, availability, quality, and safety requirements. This paper aims to describe a systematic approach for comparing design options created during the conceptual design stage of gas turbine components, based on cost evaluation and value analysis. The method allows designers to define design concepts for achieving target costs by combining functional decomposition, conceptual cost modelling, and the Value Analysis Value Engineering (VAVE) method. Functional decomposition allows identifying gas turbine modules and related components providing the main features to develop. Conceptual cost modelling is used as a decision-making design tool to predict the overall cost of gas turbine modules, and VAVE is adopted to find disruptive ideas and design changes whenever the gap between the estimated cost and the target cost is not compliant with the company requirements. The main outcome of the proposed methodology is to anticipate the cost of projects since the very conceptual stages with an acceptable level of accuracy compared with the target cost. The feasibility and the effectiveness of the proposed approach in value assessment, cost estimate, and optimization are demonstrated through a case study related to gas turbine blades. In the presented example, product value has been increased by lowering the manufacturing cost of key components while maintaining the same functions. Results highlight how the application of the proposed approach allows to reduce the overall cost of approximately 25% compared with the original design solution and to increase the product value up to 33%.

Keywords: Gas Turbine, Value Management, Product Cost Management, Value Analysis Value Engineering, Parametric Cost Estimation, Conceptual Design.

List of acronyms

BOM	Bill of Material
CAD	Computer-Aided Design
CER	Cost Estimating Relationship
CTOC	Converter, Transmitter, Operator and Control method
CTQ	Critical to Quality
DL	Direct Labor Cost
DM	Direct Material Cost
DOE	Design of Experiments
FAST	Function Analysis System Technique
NPD	New Product Development
PCM	Product Cost Management
PDP	Product Development Process
PRD	Product Requirement Document
PM	Product Manager
PO	Purchase Orders
PRD	Product Requirements Document
QFD	Quality Function Deployment
SC	Should Cost
TCO	Total Cost of Ownership
TIPS	Theory of Inventive Problem Solving
VAVE	Value Analysis Value Engineering

1. Introduction

Gas turbine development is a complex process where the design team is called to balance many requirements, starting from power and efficiency, and taking into account manufacturability, availability, maintenance, and cost. Such complexity is particularly enhanced at the conceptual design phase when a limited set of information is available, and the design space is wide. The outcome of the conceptual design for a gas turbine is a "product architecture" definition, which summarises all the technical features implemented to tackle design constraints, as described in [1] and [2]. Product architecture choice is a trade-off between target cost and other product performances which include many aspects such as manufacturability [3], assemblability [4], life cycle performance [5], environmental impacts [12] among others. A gap analysis between cost model and target cost is started in the pre-conceptual stage when the impact of the right decision on total product cost is the most efficient [13]. When a design is fixed or close to being validated, the possibility to minimize costs declines, and cost estimation becomes more accurate [14].

Over the years, several design techniques have been developed to handle cost estimation during the early stages of design. These methodologies encompass the adoption of functional analysis as part of the Value Analysis Value Engineering (VAVE) analysis [15], Theory of Inventive Problem Solving (TIPS) [16], Quality Function Deployment (QFD) [17], System Engineering (SE) [18] and few more. All the above-mentioned methodologies present benefits and drawbacks, considering the specific field of application and the complexity of the product under development. Some attempts have been made to use the above approaches in the context of gas turbine development, which is a large product containing thousands of parts and multiple manufacturing processes. Among all the methodologies proposed, the VAVE is the one that fits better the application on gas turbine design, while the others showed some limitations. Product complexity, supply chain management, intellectual property, and many other factors are only a few aspects that affect the product analysis in the early stage of engineering design. As stated in many research works [19][20][21][22], a systematic approach which couples different design methodologies (concurrent design) would be beneficial to support the decision-making process related to the gas turbine product and the constituent components.

This paper aims to describe a systematic approach for estimating the cost of design solutions developed for gas turbine products and components in the early phases of product development (conceptual design), integrating functional decomposition, conceptual cost modelling, and the VAVE analysis. The presented approach was developed through a collaboration between the research staff members of technical university/academia and a technology provider (company) operating in the oil and gas field. Two main novelties arise considering this approach. The first one refers to the ability to combine cutting-edge approaches (e.g., VAVE) with dedicated tools established for the specific field of gas turbines (e.g., conceptual cost modeling), addressing product cost in the early stages of design and making use of existing data. The second one refers to the conceptual cost modelling which split the product cost into two main contributions: direct material cost (DM), which is related to raw materials or semi-finished products, and direct labor cost (DL), which includes all machining, heat treatment, coating, and inspection contributions required to achieve final product geometry. These two cost centers are characterized by dedicated cost models that are described within the paper. Despite the fact that this split is common in the definition of parametric cost models, using DM and DL in the VAVE analysis aids in the characterization of component functions with the goal of capturing a higher level of detail (i.e., the cost associated with each function in a given design solution) once material and manufacturing processes are chosen. DM and DL allow allocating functions based along the production stages, analyzing material and geometry functions (DM) and production process functions (DL) with the associated costs. A case study (gas turbine blades) is presented following the application of the integrated approach as part of the overall design of a new gas turbine. A conceptual costing model for gas turbine blades was developed, considering all cost factors and analyzing the level of confidence related to the developed methodology. The overall value of the turbine blade module was increased (up to 33 % compared to the original design) by reducing component costs by approximately 25% while keeping the same functions.

Following this introduction, Chapter 2 (state of art) illustrates a literature analysis related to design methodologies for product development in the conceptual design phase, focusing on the specific sector of gas turbine and highlighting the limits of the proposed methodologies. Chapter 3 (materials and methods) describes the systematic approach for cost estimation and design optimization of gas turbine components, including the parametric cost estimation approach and the VAVE methodology. Chapter 4 (case study) presents the case study of gas turbine blades product analyzing in detail each step of described methodology. Finally, Chapter 5 (results and discussion) highlights the main benefits and limitations of the methodology and Chapter 6 (conclusions) summarizes the main outcomes including future development on this topic.

2. State of Art

Impact about cost reduction is extremely important at the conceptual stage, with the large design space to investigate and different alternatives (product architectures) to compare. The definition of a product architecture begins with the arrangement and layout of modules, as well as a preliminary analysis of each component's manufacturing processes [23][11]. Because more than 70% of a product's cost is committed during the conceptual design stage [24], it is critical to estimate and optimize costs as early as possible since any future changes will have an influence on re-design efficiency and the procurement time. Literature highlights that two main topics were addressed for answering the issue of cost control during the conceptual design of a product: (i) functional and modular decomposition for product families and architectures definition [18][15], and (ii) cost estimation models developed in accordance with available information and uncertainty analysis [25][26].

Dealing with the first topic (functional and modular decomposition), several design methodologies were developed in the last decades to support the engineering analysis of modules and their definition. Functional analysis [27] allows the modeling of a general product framework for the development of engineering choices. Functional analysis is used to formalize product functions at the conceptual level, and it is frequently used with module heuristics to define functional modules. [28][29]. Product architecture and related interfaces are defined using functional modules, which meet project requirements while lowering overall costs. [30][19]. Functional decomposition is applied to several areas of interest, from product to process, following a systematic step-by-step process and leveraging a multidisciplinary approach. Theory of Inventive Problem Solving allows improving generation of creative and disruptive ideas providing a means to enrich the solution space [16] [31]. This approach provides a highly valuable framework for breaking designers' conventional mindsets, but it has a few drawbacks as a non-systematic process, such as low reproducibility of created solutions [31]. QFD is a customer-oriented approach, which considers many aspects (e.g., costs, quality, reliability) in a qualitative way, missing a detailed analysis and assessment of cost breakdown [17]. QFD ensures quality control during the manufacturing process, although it is more focused on planning than with design [32] and it isn't explicitly oriented toward cost estimation [17]. The system engineering method is a requirement-oriented process that follows a rigorous approach which is time-consuming and needs certified system experts to be correctly applied [18]. The system engineer enables a shift in perspective in order to obtain a good understanding of the product and to examine both the short- and long-term effects of actions [33]. CTOC method (Converter, Transmitter, Operator, and Control) is a systematic procedure that guarantees a transition from function to physical architecture as described by [34] and applies mathematical formulas to describe physical phenomena as stated in [35]. Limitations of the CTOC approach is its applicability in modelling systems that are not presenting energy flows [34][35].

The VAVE methodology shares system analysis and decomposition with the CTOC method; however, the VAVE methodology allows investigating design solutions and cost allocation to the specific product requirement [36][37][38][39][6][7]. The VAVE is a systematic approach and leverages advantages of a multidisciplinary approach but, as per system engineering, needs certified experts to be correctly executed [33][18][15][10]. A summary of the advantages and drawbacks of the design methodologies used for functional and modular decomposition is reported in Table 1.

Table 1: Advantages and Drawbacks of design methodologies used for functional and modular decomposition - © Company, LLC - All rights reserved.

Functional decomposition methodologies	**Advantages**	**Drawbacks**
Theory of Inventive Problem Solving (TIPS)	Allows Creative/Disruptive idea generation and provides intuitive means to clarify solution space [16] Breaks designers' conventional mind-set [31]	No repeatable process/solution [16] Lower focus on service application with respect to tangible context. [31]
Quality Function Deployment (QFD)	Customer Oriented [17] Guarantees quality assurance during production phase [32]	Not specifically focused on cost [17] More focused on planning than on design [32]
CTOC	Systematic procedure that guarantees transition from function to physical architecture [34] Applies mathematical formulas to describe physical phenomena [35]	Not optimized for modelling systems without energy flows [34][35]
System Engineering	Requirements oriented [15] Change perspective to increase understanding [18] Consider both short-term and long-term consequences of actions [33]	Need System certified experts to be executed [18] Long time to be developed [15]
VAVE	Cost included in analysis Creative/Disruptive idea generation [15] Multidisciplinary approach [33] Systematic process [18]	Long time to be developed [15] Need VAVE certified experts to be executed[18]

Dealing with the second topic (cost estimation methods), literature is plenty of design methodologies and tools focused on the cost estimation issues [40][41][42][43][44]. Cost estimation is defined as a design activity able to assess the cost of a product before it is manufactured [20][1]. Cost estimation is performed through the definition of a mathematical model which integrates and combines the cost items [45]. Methods used in literature for cost estimation can be distinguished: (a) qualitative methods, which calculate product cost with respect to previously developed design and, (b) quantitative methods, which estimate product cost analyzing design characteristics and manufacturing steps required to make the component [46]. Quantitative methods are the preferred choice for product cost evaluation during the conceptual stage in terms of accuracy and reliability [21]. The main advantages of qualitative methods are that they can be used from the early stages of a project as well as the possibility to apply them to unpredictable and non-linear problems; however, the main drawback is the lower accuracy with respect to quantitative methods. Quantitative methods, on the other hand, need detailed information and a higher level of complexity in development in order to reach a higher accuracy and to be able to identify all cost drivers. The advantages and drawbacks of these methods are summarized in Table 2.

Table 2: Advantages and drawbacks of design methodologies used for cost estimation - © Company, LLC - All rights reserved.

Cost estimation methodologies		**Advantages**	**Drawbacks**
Qualitative Methods	Intuitive techniques	Applicable from preliminary stages,	Complex development [33]

		Innovative design approach [1]	Accuracy not evaluable cause the results are always dependent on the estimator’s knowledge [47]
	Analogical techniques	Applicable from conceptual design stage, fits uncertain and non-linear problems [1]	Accuracy lower than 30% [47][48]
Quantitative Methods	Parametric techniques	Cost driver identification [1]	Complex development [1]
	Analytic techniques	Easier method [1]	Require detailed design information [1]

Due to lower accuracy, qualitative methods are not preferable to quantitative ones. Furthermore, a methodology with a 30 percent accuracy will not be able to meet the goal of achieving an estimation gap of less than 10%. Quantitative methods, on the other hand, may meet accuracy requirements, but they require proper inputs starting with the conceptual phase [8]. Since that inputs are not always available, it is hard to use such methods "as-is" without having dedicated customization. Quantitative methods are inconsistent with the purpose of the study, which is to identify a minimum set of cost drivers that will allow for accurate cost prediction (estimation gap lower than 10%). In addition, cost models already developed with general-purpose or dedicated to a specific field of application cannot be applied due to the fact that gas turbine components have a proprietary design with specific features and technologies that needs a dedicated costing model to be analysed [9].

With regards to the two topics, a few attempts have been made to merge functional/modular analysis and cost estimation with the aim to build an optimized product architecture. Rehman and Guenov proposed a hybrid approach which incorporates case-based reasoning to cost estimation at conceptual design allowing the evaluation of such designs through a cost function [40]. Saravi et al. used the Design of Experiments (DoE) to collect information in a more effective way with the aim to estimate the product cost [44]. The use of DoE allows finding the optimum design solution with a high level of confidence in the cost estimation. On the same aim, manufacturing cost estimation methods dedicated to specific manufacturing technology were deeply investigated as described in [49][14][50][51][52], and life cycle impact was often included in the analysis [53][54]. Among those methods, parametric cost model approaches were considered robust models in the definition of cost centers for different manufacturing technologies, providing a gap between estimated and actual cost near the 10-15% [55][56].

3. Materials and Methods

The presented methodology is fully integrated with the traditional product development process (PDP) proposed by [27] and it focuses on the conceptual design phase. The overall framework of the methodology is presented in Figure 1. The methodology flowchart is characterized by two main streams: the first one called “Parametric Cost Estimation” and the second one called “VAVE”. It is worth noting that the second stream is only used when, after completing the Parametric Cost Estimation stream, the gap between the estimated cost retrieved by the first stream and the target cost is higher than 10%.

The first stream, Parametric Cost Estimation, is composed of five steps that are described in detail in section 3.1. Within this stream, a parametric approach for cost estimation is used based on regression algorithms (i.e., linear, quadratic, and cubic) and data coming from company knowledge. Parametric cost curves are then obtained and R^2 is calculated to check data quality and curve reliability (i.e., only R^2 higher than 0.85 is acceptable based on the company internal practice/standard). Estimated product cost is analysed against target cost which is usually set by market price and business requirements. Once the first stream is completed, two branches are possible. The first branch is followed when the gap between the estimated cost versus the target one is lower than 10%. In this case, a formal review of the given product design is possible, and cost items are managed in accordance with all other performance parameters, with the goal of achieving the target cost. The second branch is followed when the gap between the estimated cost versus the target one is higher than 10%. In this case, the current product architecture prevents the achievement of the goal cost, requiring the development of new product architecture and module design.

The second stream (i.e., VAVE), is triggered only in this second case with the aim to reach a disruptive product/modules redesign in order to reduce cost (design to cost) and to provide several alternatives for the analysed product. Within this stream, a modified version of the VAVE methodology is adopted to analyze component design through functional analysis. The second stream is composed of five steps following which it is possible to develop a new concept and adopt new technologies with the aim to reduce and optimize product cost. Once the VAVE is completed, new design solutions for the product/modules are available. Before proceeding with the validation of the most promising solution, it is necessary to update the estimated cost using parametric costing curves. It is important to look into the existing parametric cost curves and check if they are still suitable for the new design. Then, it is possible to update the estimated cost based on an improved design using the new parametric costing curves, or previously defined curves. If the VAVE was effective in closing the gap between the estimated and target costs by at least 10%, the process can be finalized with a formal assessment of the defined design. On the other hand, if the gap is still higher than 10%, and the VAVE was already applied to the given component without success, it is necessary to check and update the target cost. Allocation of cost target among other components and subsystems is analyzed under the guidance of system engineer and, if possible, maintaining the total target cost, the increment of the component target is approved, lowering other component cost targets that can absorb the cost increment of the mentioned component. After using VAVE, if there is no room for target cost increment and the gap is greater than 10%, the team notifies the product leader that the target is not met on that specific component and reports the current gap inside the target.

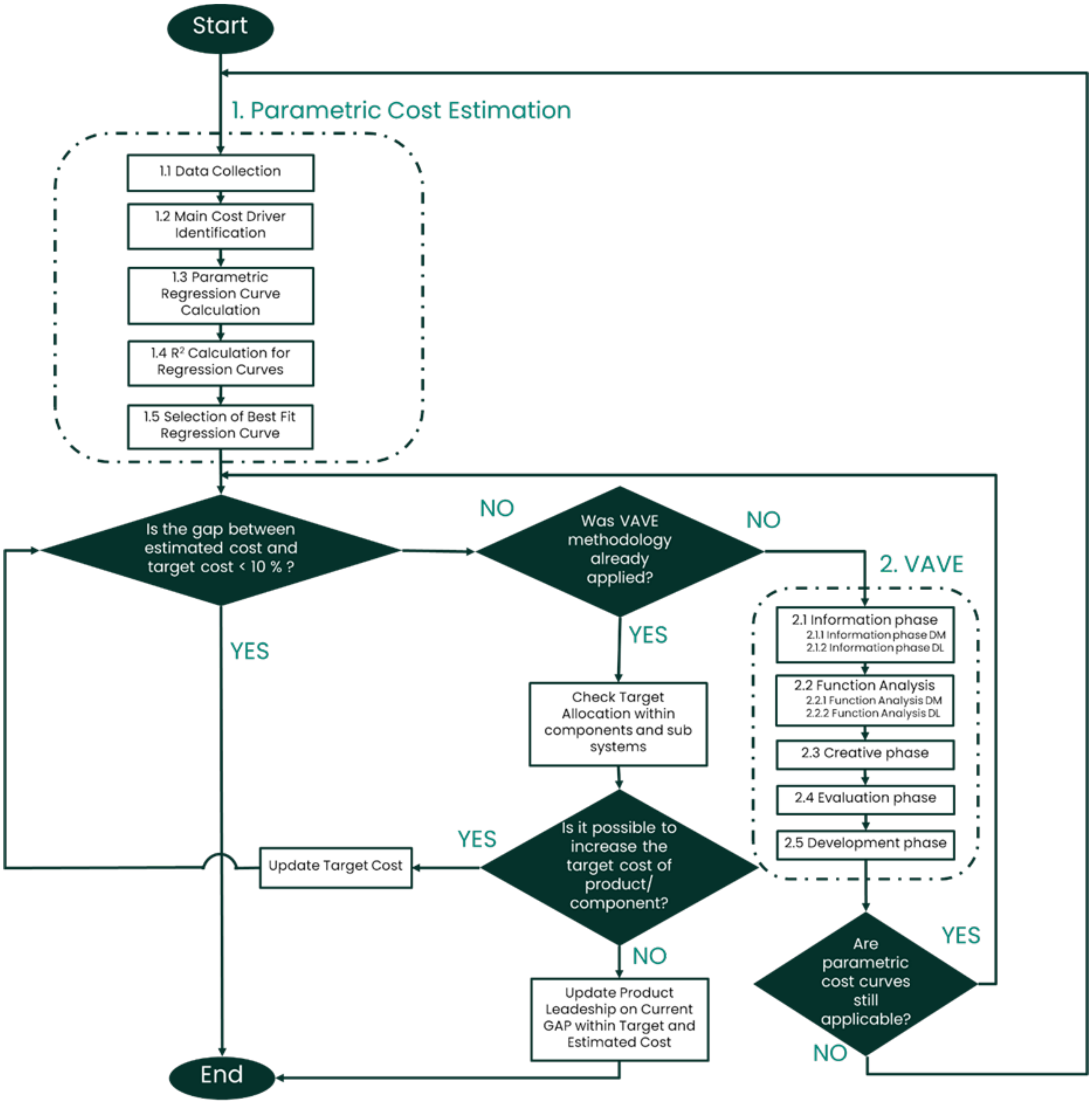


Figure 1: Flow chart decision process – GAP control and VAVE trigger - © Company, LLC - All rights reserved.

Referring to the flowchart reported in Figure 1, the description of the parametric cost estimation stream is reported in section 3.1, while the VAVE stream is described in section 3.2.

3.1. Parametric Cost Estimation

For complex products, such as a gas turbine, manufacturing and assembly activities are performed in collaboration with several companies involved in the overall manufacturing process (suppliers). The cost drivers identification is performed by value engineering through the review of internal knowledge and the analysis of the supply chain (providers) that identify the features that influence the cost of addressable parts/systems. Parametric cost models, based on historical data, are usually used for this activity, as well as a breakdown analysis of actual costs coming from existing configurations. According to internal design practice, the goal is to identify a minimum set of cost drivers that will enable to predict cost estimation with high accuracy (estimation gap lower than 10%).

The purpose of the “parametric cost estimation” stream is to leverage turbine components cost drivers with the aim to rapidly generate value analysis and to estimate cost with acceptable accuracy and a limited set of information. As known, lack of information is the main issue inherent to the initial stage of the project. To cope with this issue, the parametric cost estimation approach, applied to each part or module constituting a given architecture, allows estimating the total cost of the product. Component cost estimation requires to include for both raw material portion defined as direct material (DM), and cost of production from raw material to final geometry defined as direct labor (DL). The cost of assembly is included in the DL as part of the total product cost. Using an internal database as input, parametric cost estimating models are developed for each module and component that constitute the configured gas turbine. This database is queried to estimate the costs of various design options, making comparisons between different architectures. To this aim, the designer/engineer produces an enriched drawing or model, where enhanced drawing means that the document shall represent the geometry but also all the attributes needed for cost estimation (i.e. material selection for each component, number of blades, surface finish requirements, etc.). The parametric costing tool can then read this data and assist engineers in doing a preliminary cost analysis from the early stages of the project. Even though CAD is not typically utilized during the conceptual stage, it can help with the evaluation of different architectures in some cases, thanks to simplified digital mock-up comparisons and/or a simplified version of previously developed CAD models. Inputs, automatically imported from geometrical features or manually identified by designer/engineer are elaborated through parametric cost curves to estimate part value. Figure 1 describes the process steps involved in the "parametric cost estimation" stream, which are detailed here below.

Step 1.1 – Data Collection. Data from past projects is collected considering a common family of products/components (modules). This is the first step of the “parametric cost estimation” block and it allows to create a repository for the parametric cost models based on previous purchase orders (PO). Data must be collected and classified on a cost items basis. The contribution of numerous cost drivers determines the final value of the PO, hence organized storage of purchase orders is done with the most relevant cost drivers in mind. This data collection and classification is considered the preliminary activity for the identification of cost drivers. It is worth noting that each data included in this collection has its own history which affects the data value itself (i.e., current market trend and external factors, raw material cost fluctuation, bundle volume, acceleration fees). All these aspects are tracked in order to consider them in following steps of analysis. Updating data and outcomes necessitates database maintenance and, as a result, cost model maintenance. When new orders are placed and new quotations are addressed, the related cost curves will be updated over time as new data points are introduced.

Step 1.2 – Main Cost Driver Identification. The first draft of the cost model is built with a preliminary classification of cost drivers. Cost drivers are identified starting from geometrical attributes and technological parameters of components. The cost contribution of each parameter is detected and segregated from the aggregate total cost of Step 1.1 (data collection) in order to proceed with a parametric costing curve assessment once the cost drivers for each component have been determined. The first contribution to be identified is material cost (DM), followed by production processes cost (DM) such as machining, coating, heat treatment, etc. All of these contributions allow for the development of parametric cost curves and the identification of a set of cost drivers for component costs. The aim of this step is to find correlations among cost drivers and to identify the recursive drivers that can be generalized.

Step 1.3 – Parametric Regression Curves Calculation. Based on the identified cost drivers and the data collected in the previous steps (data set), parametric cost curves are mathematically defined. For the sake of simplicity, the cost curves take into account only one parameter at a time (cost driver) vs. the cost. Three models (curves/graphs) are retrieved using a single set of data for each cost driver: (i) a linear regression model, (ii) a quadratic regression model, and (iii) a cubic regression model. The choice to adopt these three mathematical regressions is driven by the need for a simple tool to estimate parametric curves providing the best fitting with the available data.

Step 1.4 – R^2 Calculation for Regression Curves: For each one of the three costing curves calculated at Step 1.3, the related R-squared (R^2) value is assessed. R-squared is a measure of data fitting by a regression line and it gives information on the goodness of the regression predictions in approximating the real data points. R-squared has values ranging from 0 to 1, the higher the R-squared, the better the regression curve matches the data points. R-squared calculation is critical for having numerical information on regression curves reliability, and for turbomachinery components, only R-squared larger than 0.85 is regarded as a good correlation, according to internal business practice.

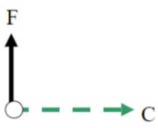
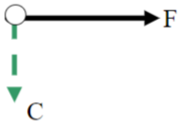
Following the evaluation of R-squared for each of the three models, the greatest R-squared referring to the curve that best fits the historical data is chosen and presented in the next phase.

Step 1.5 – Selection of Best Fit Regression Curve: Based on the results of step 1.4, the fitting curve with the higher R-squared is selected. Thresholds for an acceptable R-squared value are set by the company based on internal knowledge and the level of accuracy that the company wants to attain. For this reason, R-squared higher than 0.85 is considered to be a very good correlation according to the engineering activity and internal quality standards. R-squared values ranging from 0.6 and 0.85 are an acceptable correlation that can be further refined with additional data or investigating the quality of the given data. R-squared values lower than 0.6 require a deeper investigation to increase cost model accuracy. Finding the proper cost regression curve is not always a process that requires the application of a mathematical model. To better understand the process and the impact of the contribution of each cost item, a deeper analysis is required. The supply chain, for example, and the selection of different suppliers are aspects that should not be overlooked when evaluating these cost curves. On this aim, each machining phase of a cycle requires to be described in terms of base operations and evaluated through a specific parametric equation. For each machining type, several parameters are taken into account inside the parametric cost model, to be able to predict cost in case of new orders. In particular, set up hours are considered with their relative cost, machining cutting phase as well as time and cost related to inspections, packaging, and shipment.

3.2. VAVE

The VAVE (Value Analysis, Value Engineering) is an organized step-by-step procedure which allows to increase the value of a system of interest. It leverages the function analysis and aims to increase the ratio between functions performed and the resources needed to achieve them. There are various ways to increase the value of a product, and each of the five alternatives listed in Table 3 can be pursued.

Table 3: Different strategies to improve product value - © Company, LLC - All rights reserved.

					
	a)	b)	c)	d)	e)
Function	Increase	Remain Constant	Increase	Increase	Decrease with a lower rate
Cost	Remain Constant	Decrease	Decrease	Increase with a lower rate	Decrease

Functional decomposition allows identifying product modules and related components providing the main features to develop through the design activity and key manufacturing aspects to fulfil. Conceptual cost modelling is used as a decision-making design tool to predict the overall cost of the module/product under investigation, providing, as output, the gap between the estimated product cost and the target cost. When this gap does not allow to guarantee the target cost (i.e., the gap is higher than a given threshold), the VAVE is adopted to find disruptive ideas and design changes that allow to reach the target cost and consequently increase the level of confidence (uncertainty) related to the estimated cost. Finally, multiple design choices developed during the conceptual design stage are evaluated based on the aim of the proposed method to select the one that achieves the target cost while meeting all performance requirements (desired functionalities). Another noteworthy aspect of the VAVE is that the identification of several design options and the selection of the most promising ones are obtained by teams composed of members with various backgrounds, to bring both innovative ideas and expertise on the subject matter. The five-step of the VAVE methodology is introduced in section 3.2, following the standard approach described in [18] and [15] and modified to take into account specific aspects related to the turbomachinery design. The VAVE methodology was defined by SAVE International (Society of American Value Engineers) in six phases. The standard VAVE methodology has been adjusted to fit to the turbine components for the specific product and context (turbomachinery). The first two stages of the methodology were split into two dedicated paths dealing with DM and DL. In fact, the cost of gas turbine components is split evenly between DM and DL, which indicates that each part of the cost may be thoroughly investigated if evaluated independently. Moreover, the overall number of steps was reduced from six to five.

- **Step 2.1 - Information Phase**. This phase allows gaining a deep understanding of the project, system, process, or study item. The Value engineer shares all the material collected and prepared during the pre-workshop activities and the tools needed to be used during the VAVE Workshop. The following are the tasks to be completed during this phase:
    - To present background information to the whole team of work;
    - To identify key stakeholders and share targets for design to cost;
    - To present current design information (leveraging most experienced team members/experts on the subject);
    - To recognize known constraints on the current design, that shall be met also by future redesign alternatives;
    - To identify the study subject and related design team contacts, to provide supporting documentation, and to respond to any inquiries that may arise.

All the information collected in this phase is useful to define product value with the current design. This value will be compared to the value of the product which encompasses redesign recommendations at the conclusion of the VAVE application, and the relative advantage will be emphasized. According to [18] and [15], and based on the European Standard EN1325:2014 [57], Value is defined as the consistent performance that a product or process must achieve in order to operate and sell at the lowest possible price. The following equation is used to express the product value analytically (equation 1):

$$Product\ Value = \frac{Requirements\ Satisfaction}{Product\ Cost} = \frac{Function}{Cost} \tag{1}$$

- **Step 2.2 - Function Analysis Phase**. This is the most complex and time-consuming step of the VAVE methodology and it is fundamental for the success of the VAVE Workshop. In particular, this phase can be divided into the following actions:

Identify Functions: it identifies all verb-noun combinations that can be used to express the functions of the subject under investigation. It can be seen as the product functional analysis and it needs to be carried out according to the syntax outlined in the VAVE approach [15].

Classify Function: it classifies functions (i.e., higher-order function and lower-order function) based on the scope of each function. The higher-order functions, for example, describe the requirement that causes the existence of the basic function. The basic functions of a product describe the exact tasks that it is meant to perform (as intended), while secondary functions describe all other functions that the product performs (auxiliary functions). The lower-order function describes functions that are outside of the scope of the study, such as the inputs to a project, product, or process that are not included in it. Another possible classification of functions concerns: (i) required functions, which are needed to fulfill basic functions, (ii) aesthetic functions, which are often used to help sell a product to customers, and (iii) unwanted functions, which are related to unwanted processes that occur concurrently with required functions. Some of the functions identified are linked to design specifications or functions that occur only once or often throughout the component's life cycle; these functions are cataloged in the upper portion of the Function Analysis System Technique (FAST) diagram.

Allocate resources to Functions: It meets the requirements of the Function-Resource matrix. Function-Resource matrix is a table that that shows how many resources are required to complete each function. This matrix allows ranking the functions in terms of cost to obtain them (with current design). Once the cost for each function is calculated, it is possible to prioritize functions based on their cost and identify opportunities for value improvement. The goal of this stage is to figure out which functions have room for improvement in terms of value. It is recommended to focus on the functions with the highest costs and that can account for at least 70% of total component cost. As part of the methodology's evolution, two FAST diagrams are developed, each with its own set of functions and costs (i.e., DM and DL FAST diagrams). Each function's cost is expressed as a percentage of the cost portion of the FAST diagram (DM or DL) as well as the total component cost. Before proceeding with the processes from stage 2.3 to stage 2.5, the cost functions with the largest impact on the total cost are chosen. Some of the functions developed, (i.e., for the machining process of for the coating), cannot be clearly identified without this deeper investigation. In fact, by focusing solely on the component, all aspects of the manufacturing process and related tasks are overlooked.

- **Step 2.3 - Creative Phase**. The aim of this step is to generate a large quantity of ideas or alternatives to accomplish the functions identified in the previous phase. Within this step, all the team members are required to generate several ideas for each function identified. However, all the proposed ideas are not evaluated by the team during this phase. All of the ideas are gathered on a flip chart with the goal of assisting the team in coming up with new ideas in a brainstorming session. As explained by [15], the process of idea generation requires the generation of at least 80 alternatives. It is an important amount of ideas, but it is necessary to generate also disruptive and emerging ideas, with aim to improve the function under investigation.

- **Step 2.4 - Evaluation Phase**. This phase aims at the evaluation (engineering judgement) of the ideas generated during the creative phase. The selection of the most promising concepts, which will be developed in the development phase, is the result of this process. It is possible to sort all the ideas by using the following rules:
  - Ideas classification: by grouping together ideas that refers to the same area, such as “material change” or “new technology introduction” or “geometry modification” and so on..
  - Ideas ranking: by categorizing ideas according to their influence on product cost.
  - Ideas integration: by coming up with new concepts based on a synthesis of several ideas (obviously choosing not mutual exclusive ideas).

The output of the Evaluation Phase is a list of selected ideas, that from this stage will be called “proposal” ready for development.

- **Step 2.5 - Development Phase**. The goal of this phase is to engineer the selected ideas into design concepts that will improve the product value. Only a preliminary analysis is carried out at this stage, and the detailed engineering study being postponed on a later phase. Equation 2 is used to evaluate the influence of design option on the product value. According to the equation 2, *Requirements Satisfaction* refers to satisfaction of customer needs while *Product Cost* refers to all the cost related to raw materials, labor, time, etc. [33].

$$Product\ Value = \frac{Requirements\ Satisfaction}{Product\ Cost} = \frac{\prod_i 1 - \frac{|Requirement\ Value_i - Design\ Value_i|}{Requirement\ Value_i}}{\frac{Estimated\ Cost}{Target}} \tag{2}$$

Where:

- $\textit{Requirement Value}_i$ is the value set as per Product Requirement Document (PRD),
- $\textit{Design Value}_i$ is the value assumed by the same variable “i-th” as per proposed design of component,
- *Estimated cost* is the cost evaluated during the design process steps, and
- *Target* is the target cost defined in PRD.

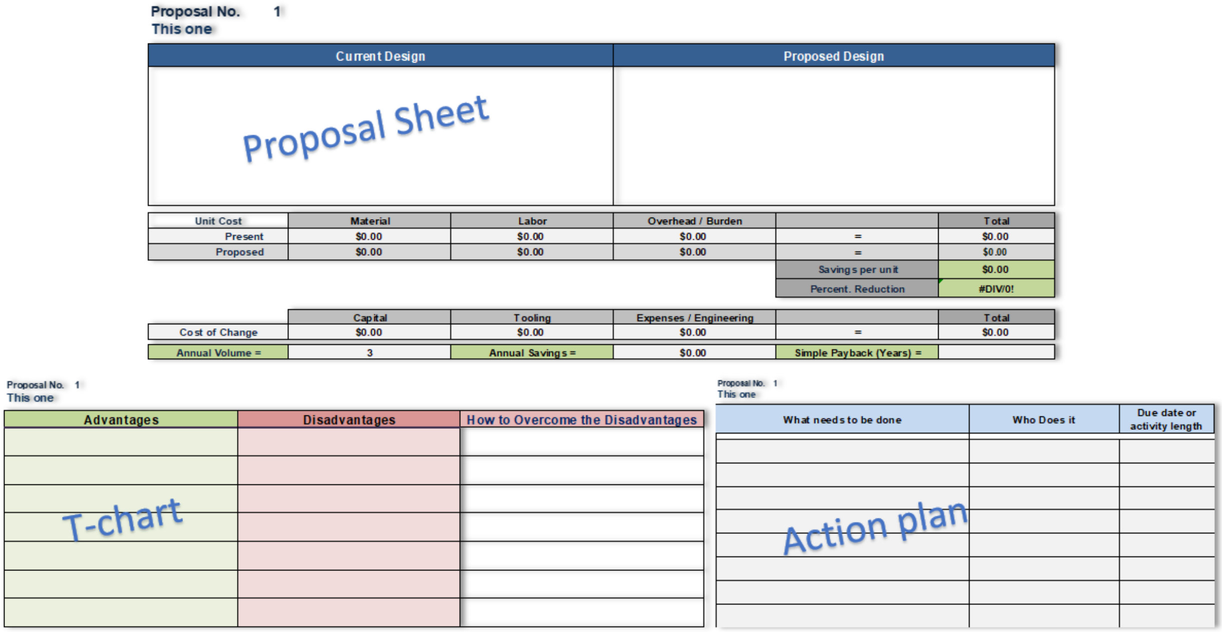
This equation is valid when $\textit{Design Value}_i$ parameter is between zero and two times the $\textit{Requirement Value}_i$. For all the other values of the $\textit{Design Value}_i$ parameter, the equation is set equal to 0, and consequently, also product value is 0 since the i-th requirement is not reached.

Product Value assumes the form of a coefficient that can be calculated at different stages of project steps to identify improvements in component value as described in [15] and [33]. Product value is a key indicator in the analysis of new products as well as in the definition of target costs.

In some cases, after the creative phase and before moving on to the evaluation phase, the team may decide to hold a new session to review and analyze the components which require a redesign (i.e., drawings and 3D models). This intermediary session is highly beneficial and therefore should be completed as soon as possible after the function analysis phase. The VAVE session concludes with the release of an action plan. After the design review, all the impacted documents (drawings, 3D models, etc.) are issued or revised accordingly. Every proposal includes the following information for a final trade-off analysis:

- Proposal Sheet: with description of selected idea, comparing current and proposed design. For each proposal, the multi-disciplinary team must evaluate the impact of change, estimating the effort and the return.
- T-chart: with the list of all the advantages, disadvantages, and possible solutions related to the selected idea.
- Action Plan: with feasibility analysis, timing and cost. The activities must be completed within the Design to Cost slot that was previously defined.

A proposal format is indicated in Figure 2.



Proposal No. 1
This one

Current Design	Proposed Design

Unit Cost	Material	Labor	Overhead / Burden		Total
Present	$0.00	$0.00	$0.00	=	$0.00
Proposed	$0.00	$0.00	$0.00	=	$0.00
				Savings per unit	$0.00
				Percent. Reduction	#DIV/0!

	Capital	Tooling	Expenses / Engineering		Total
Cost of Change	$0.00	$0.00	$0.00	=	$0.00
Annual Volume =	3	Annual Savings =	$0.00	Simple Payback (Years) =	

Proposal No. 1
This one

Advantages	Disadvantages	How to Overcome the Disadvantages

Proposal No. 1
This one

What needs to be done	Who Does it	Due date or activity length

Figure 2: Proposal sheet, T-chart and Action plan templates - © Company, LLC - All rights reserved.

4. Case Study

The methodology described in the previous section was applied to the majority of the components that constitute a new gas turbine project. This specific case study is related to a new gas turbine product designed for LNG mechanical drive, but also well suited for simple-cycle, cogeneration, and combined-cycle power generation without the need of a gearbox, for both onshore and offshore applications. For the sake of brevity, in this paper, only a detailed presentation of the application of the methodology to the turbine blades (Figure 3) is provided. Turbine blades are the components that allow the turbine flow-path of a turbomachine (both gas and steam turbine). Through blades, it is possible to extract energy from the high temperature and high-pressure gas coming from the combustion chamber or to increase the pressure of gas in the axial compressor. Turbine blades need to satisfy many mechanical and life cycle requirements and often use high performances materials and apply many different cooling methods (internal cooling, external cooling, thermal barrier coatings).

Figure 3 Example of blades - © Company, LLC - All rights reserved.

It is possible to optimize and evolve the geometry for the specific application field by starting with an existing design (past projects). Blades can be obtained by different manufacturing processes, depending on the size and raw material of a specific blade (i.e., forging, machining, and investment casting). Machining cost, which is related to the amount of material removed from raw to final geometry, can be estimated with parametric costing curves for the following parameters: blade height and the type of blades. Parametric estimation cost will be the sum of each cost contribution, starting from raw material cost (DM) and adding machining, heat treatment, coating, inspections, and so on (DL). Cost Estimating Relationship (CER) is obtained by the sum of all contributions to cost C_i applicable to the specific blade's project.

4.1. Parametric Cost Estimation for Turbine and Axial Compressors Blades

The total cost of the blades can be estimated by two main contributions using parametric costing curves as described in Step 1 of Figure 1. The first contribution is raw material cost (DM), which can be investment casting, forged component, or bar, depending on the blade type, generally supplied by external partners (farm-out), while the second contribution is due to all the machining and manufacturing steps (DL) needed to obtain final geometry (i.e. coating, heat treatment, inspections, etc.). After the cost data has been retrieved and placed in the database (Step 1.1), the manufacturing costs transfer functions are created. The goal of this stage is to generate equations that will replicate cost results with the best accuracy, identifying all the involved cost drivers (Step 1.2). At the end of this activity, every single manufacturing operation of the overall manufacturing process will have one equation associated with it (Step 1.3). It is worth noting that the cost curves are retrieved considering the analysis of manufacturing processes related to a given component (the blade in this use case). Indeed, it is not possible to set up a general rule valid for a manufacturing process independently from the type of component/module. Raw material parametric curves (for DM portion of the cost) have been calculated by aggregating data into groups, depending on the main technology adopted for the production of the blades (i.e., forging, machining, and investment casting) as well as the material constituting the blades. Considering that, the two main cost drivers are *technology* and *material*. Starting from these two main drivers, other secondary cost drivers are identified. For example, when raw material is melted to realize the final shape of the component (i.e., investment casting), the "blade's weight" is considered a secondary cost driver associated with the main cost driver *material*. On the other hand, when raw material derives from a bar (i.e., machining and forging), blade's height" is the most suitable secondary cost driver associated with the main cost driver *material*. Figure 4 shows the parametric costing curves related to the *blade's height* cost driver which (referring to machining and forging technologies). In particular, the graph shows four options based on different materials (A, B, C, and D). For the sake of data confidentiality and intellectual property disclosure, results have been plotted on the dimensionless scale for both cost and blade height.

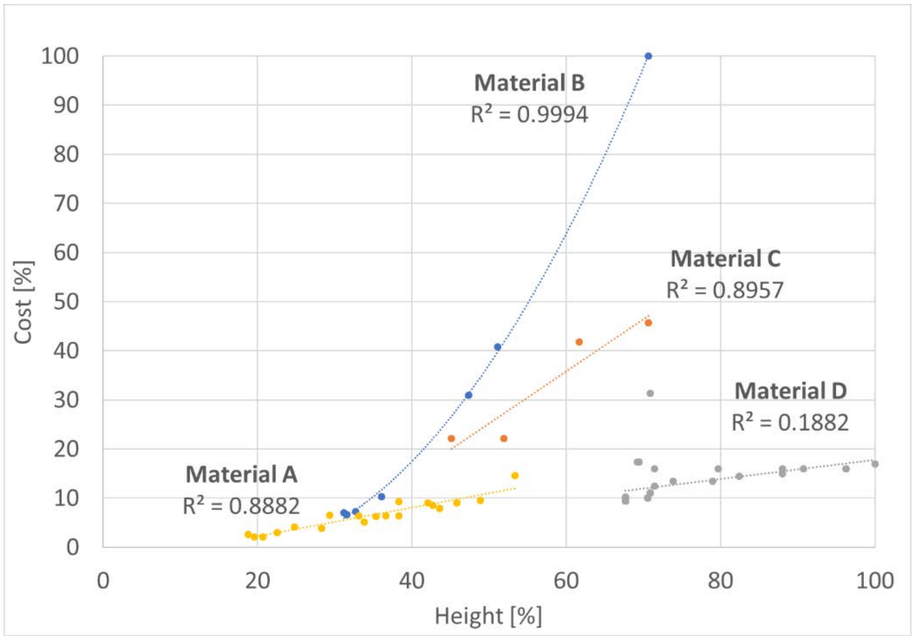


Figure 4 . Blades Raw Material Cost Vs. Height (original curves including all data) - © Company, LLC - All rights reserved.

Material A, Material C, and Material D have linear regression characteristics, whereas Material B has quadratic regression characteristics. For materials A, B, and C, R2 values show that an accurate correlation has been achieved; however, the material D regression curve is poorly accurate (R2 lower than 0.85). The weak correlation for the Material D may have several causes. In this case, three POs were affected by acceleration fees needed to lower the lead time of components on the critical path of crucial projects, and one other PO was set with a large material batch size which affected the unitary cost of the specific order. After this analysis, the outlier points were excluded from the analysis. According to this refinement, and repeating steps 1.4, 1.5, and 1.6, a new parametric cost curve for raw material D was retrieved. As shown in Figure 5, R2 increases from 0.19 to 0.88 for the cost curve of Material D, which is considered an acceptable value as per company standards.

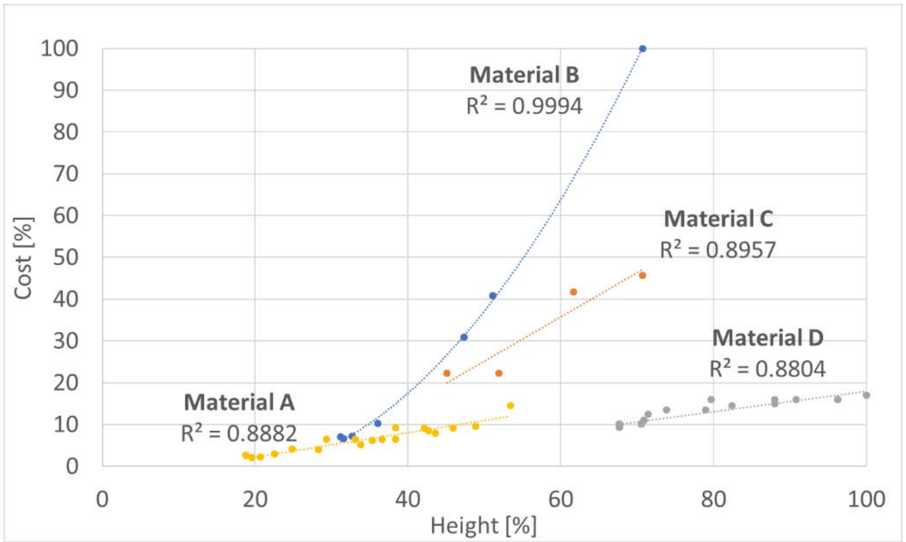


Figure 5 . Blades Raw Material Cost Vs. Height (modified curves excluding outlier data for Material D) - © Company, LLC - All rights reserved.

As a summary, all the data used for the assessment of the parametric cost curves for blades are reported in Table 4.

Table 4: Cost Contributions to CER - © Company, LLC - All rights reserved.

C_i	Technology	Input parameters	Regression Equation Type	# of Data Points	R^2
C_{rmA}: Raw Material Cost applicable only for Material A	Machining	Blades radial size (Height)	Linear	18	0.88
C_{rmB}: Raw Material Cost applicable only for Material B	Machining	Blades radial size (Height)	Quadratic	6	0.99
C_{rmC}: Raw Material Cost applicable only for Material C	Machining	Blades radial size (Height)	Linear	4	0.89
C_{rmD}: Raw Material Cost applicable only for Material D	Machining	Blades radial size (Height)	Linear	12	0.19. After Data Refinement 0.88
C_{rmE}: Raw Material Cost applicable only for Material E	Forging	Blades radial size (Height)	Linear	6	0.92
C_{rmF}: Raw Material Cost applicable only for Material F	Forging	Blades radial size (Height)	Linear	11	0.93
C_{rmG}: Raw Material Cost applicable only for Material G	Forging	Blades radial size (Height)	Linear	6	0.99
C_{rmH}: Raw Material Cost applicable only for Material H	Investment Casting	Blade Weight	Linear	7	0.95
C_{rmI}: Raw Material Cost applicable only for Material I	Investment Casting	Blade Weight	Linear	9	0.92
C_{mach}: Machining Cost	All	Cutting Speed and Delta Weight between raw and machined geometries	Quadratic	40	0.86
C_{HT} Heat Treatment Cost	All	Heat Treatment Hours	Linear	40	0.88
C_{coat}: Coating Cost applicable only if present	All	Coating thickness	Linear	32	0.85
C_{insp}: Inspection Cost	All	Number of CTQ dimensions	Linear	40	0.87
C_{pack}: Pack and Shipping Cost	All	Weight of Blades	Linear	40	0.89

A comparison of the target cost (as established by the company) and the estimated cost (as determined by this parametric analysis) was performed at the end of the "parametric cost estimation" block. For the turbine blade's module analysed in this study, the estimated cost is not aligned with the target cost, and the gap between the two costs is approximately 20%. The VAVE methodology was applied (second block of the methodology), to deeply investigate functions that the component shall perform and generate possible alternatives that guarantee the same functionality lowering cost. The authors focused on option b of Table 3, which consists in reducing product cost while maintaining and guaranteeing the same functionality in terms of efficiency and component life cycle.

4.2. Value Methodology approach on Turbine Blades

Approaching the information phase for turbine blades (Step 2.1 of Figure 1), the value engineer initiates the process to involve all the expertise available in the company, in particular from both the engineering and manufacturing departments. Internal and external benchmarking was performed, including sharing sessions about the scope of work. Preliminary 3D models and drawings revision was set, with the aim to start the preliminary phase of ideas generation. The conventional value methodology approach can be applied to a product or a process, according to the literature analysis; however, for this case study, the team decided to apply the VAVE methodology to both product and process in the same workshop. Raw material contribution to total cost (DM, raw material for blades, cost of semi-finished component) and the manufacturing process contribution to total cost (DL, machining, and coating costs) are comparable to each other, with respect to the total cost. Concerning the information phase about DM, the analysis was done with reference to the blade's semi-finished geometry and consequently, the raw material cost has been analyzed in its own information phase. On the other hand, concerning the information phase about DL, the focus was done on the machining process as well as on coating, heat treatments, inspections, corrections, and other additional processes. This phase has been also enriched by pre-workshop activities and internal and external benchmarking analyses.

Two different FAST diagrams were developed, one focusing on raw material cost (DM), and the other one related to the machining process (the process necessary to manufacture the final component from the semi-finished product (DL)). During the FAST diagram definition, it was necessary to place functions in order to answer the question "how" by moving from the higher-order functions to the lower-order functions and to answer the question "why" moving from the lower-order function to the higher-order function. In order to complete the DL fast diagram, a sort of high-level technology cycle for blades was analyzed, leveraging the expertise of the manufacturing team on previously designed blades for different machines. Step 2.2 was finalized for both DL and DM: all the functions have been identified and FAST diagrams are shown in Figure 6 and Figure 7 here below. The engineering team analyzed the functionality of both DM and DL and identified that Higher-Order functions of DM are *Deliver Performance* (of the overall gas turbine) and *Prevent Damage* (of the casing), while the Higher-Order function of DL is *Create Shape*, starting from the raw material to obtain final machined surfaces (refers respectively to Figure 6 and Figure 7). As mentioned before, the blades are designed allows ensuring gas turbine performance, while the specific need for DL is to obtain final geometry starting from raw material, through machining, heat treatment, and coating. The basic function of DM is *Guide Flow* and *Protect Component*, while the basic function of DL is to *Control Shape*. The lower-order functions, that describe functions that lie beyond the scope of the study (inputs for a project, product, or process) are *Deliver Energy* for DM and *Receive Casting* and *Receive Material* for DL.

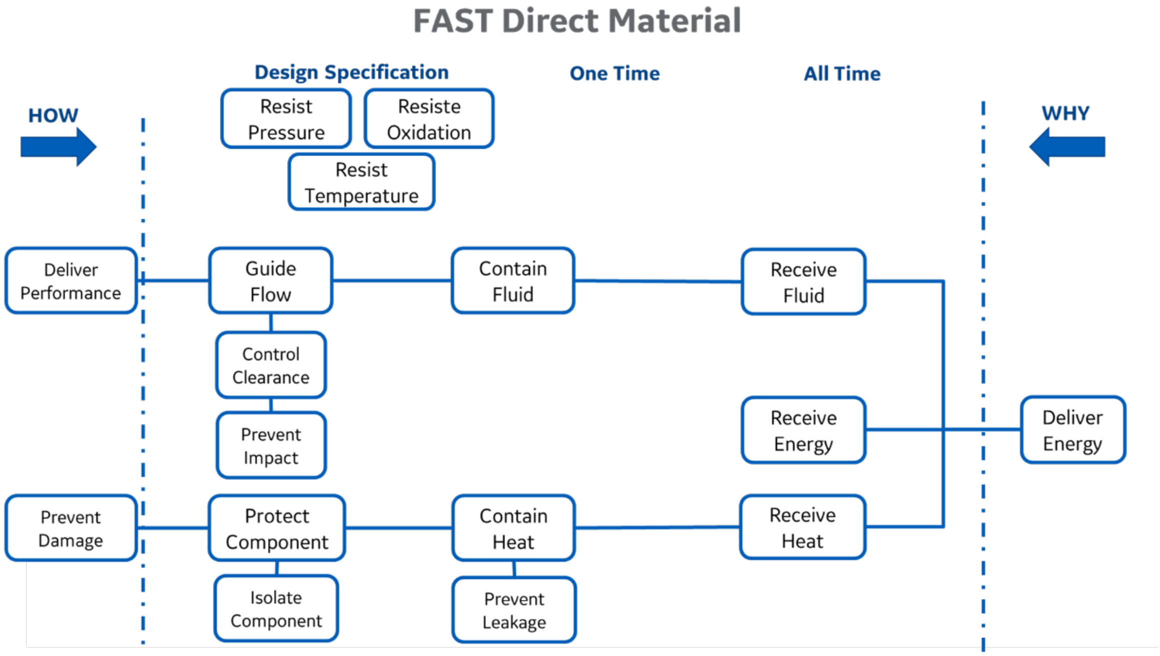


Figure 6 FAST DM - © Company, LLC - All rights reserved.

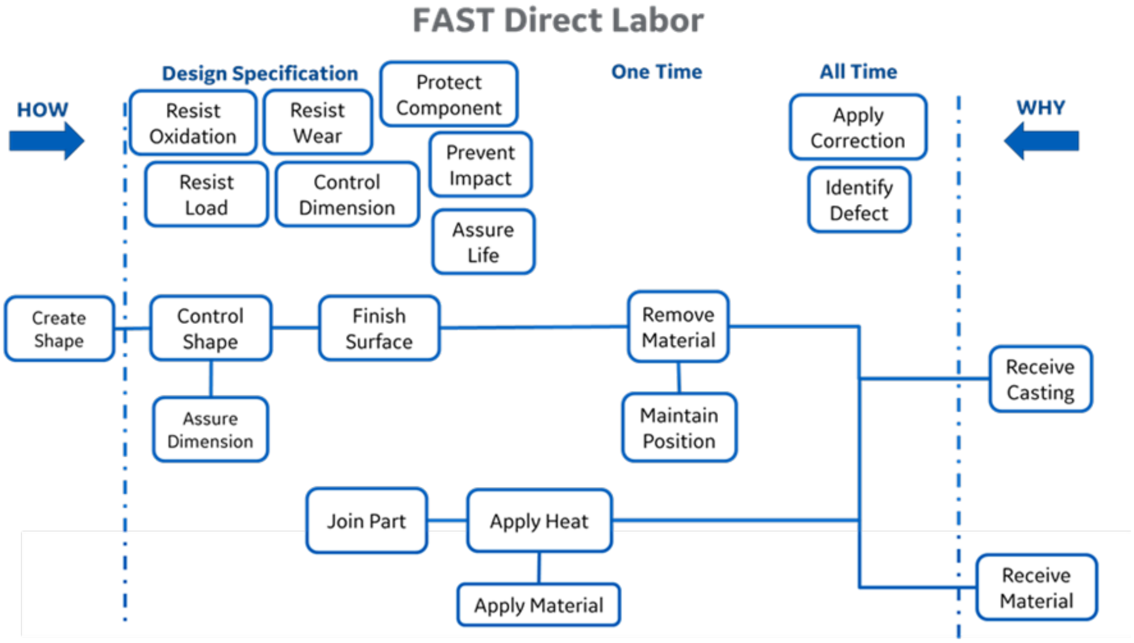


Figure 7 FAST DL - © Company, LLC - All rights reserved.

5. Results and Discussion

The accuracy of cost evaluation is affected by the missing information of this stage, often replaced by assumptions that shall be confirmed in following project stages. Cost evaluation is performed by value engineers and design engineers based on stated assumptions, and the cost estimation is shared together with the variability range. The ability of the value engineers is to predict the cost of each single process step is also related to internal supply chain capability. In the case study section, parametric cost estimation curves for gas turbine blades were presented. All the manufacturing activities performed within the company are analyzed from a cost standpoint with the support of internal manufacturing, achieving better accuracy. Supplier support is required for outsourced manufacturing processes and component production (i.e. investment casting or surface treatments that are not performed at the factory facilities). Thus, early engagement of suppliers is crucial to both predict the cost of full buy components and also to receive feedback on design, based on their expertise. Co-designing with suppliers is critical for meeting cost targets and completing cost analyses in the early stages of development without sacrificing accuracy. Following the assessment of R-squared, the accuracy concerning the estimation of blades cost between parametric and data points methods are below 3%. However, the difference between the estimated and the target cost was greater than 10%, and in this particular case equal to 30%. For this reason, value engineers supported the introduction of the modified VAVE methodology, and the gas turbine blades case study was pursued. The VAVE methodology was applied on gas turbine blades and the investment casting process was analyzed as an innovative manufacturing process for this component. The design team allocated resources to functions on each one of the two FAST diagrams, focusing both on DM and on DL. Before moving on to Step 2.3, the design team gathered all of the functions and ranked them in terms of function cost as a percentage of total component cost. As illustrated in Figures 8 and 9, the cost of functions has an impact on overall component costs (respectively for DM and DL). The main cost impacts are highlighted in red.

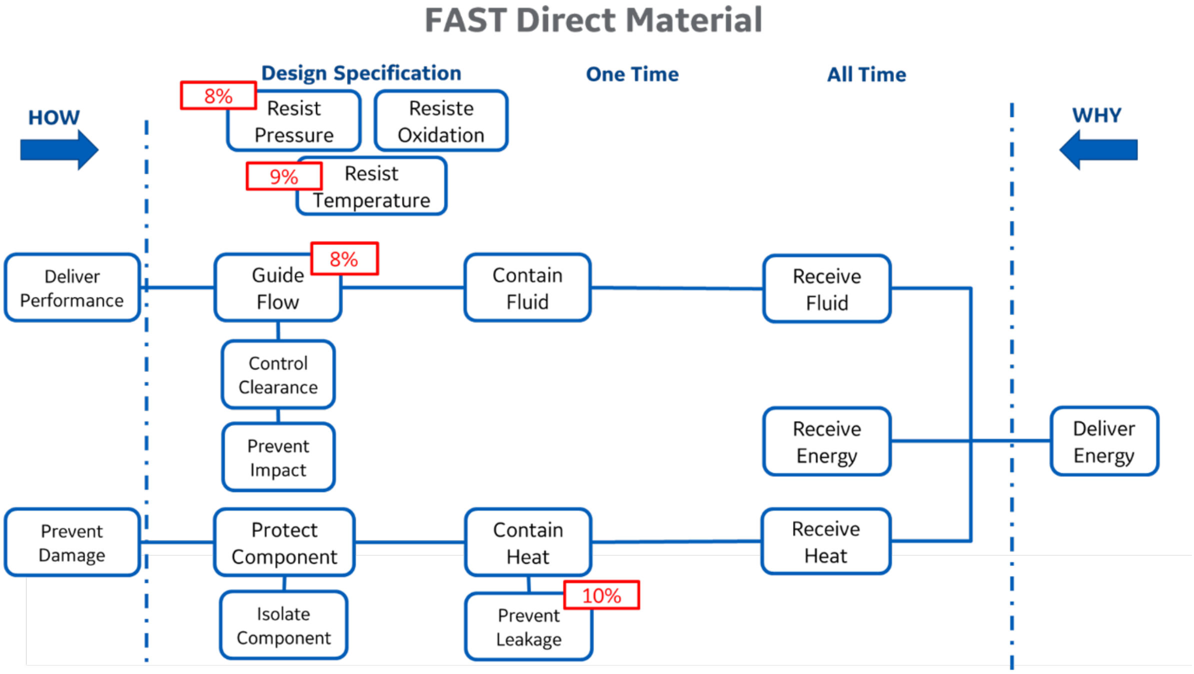


Figure 8 FAST DM for blades from investment casting technology- © Company, LLC - All rights reserved.

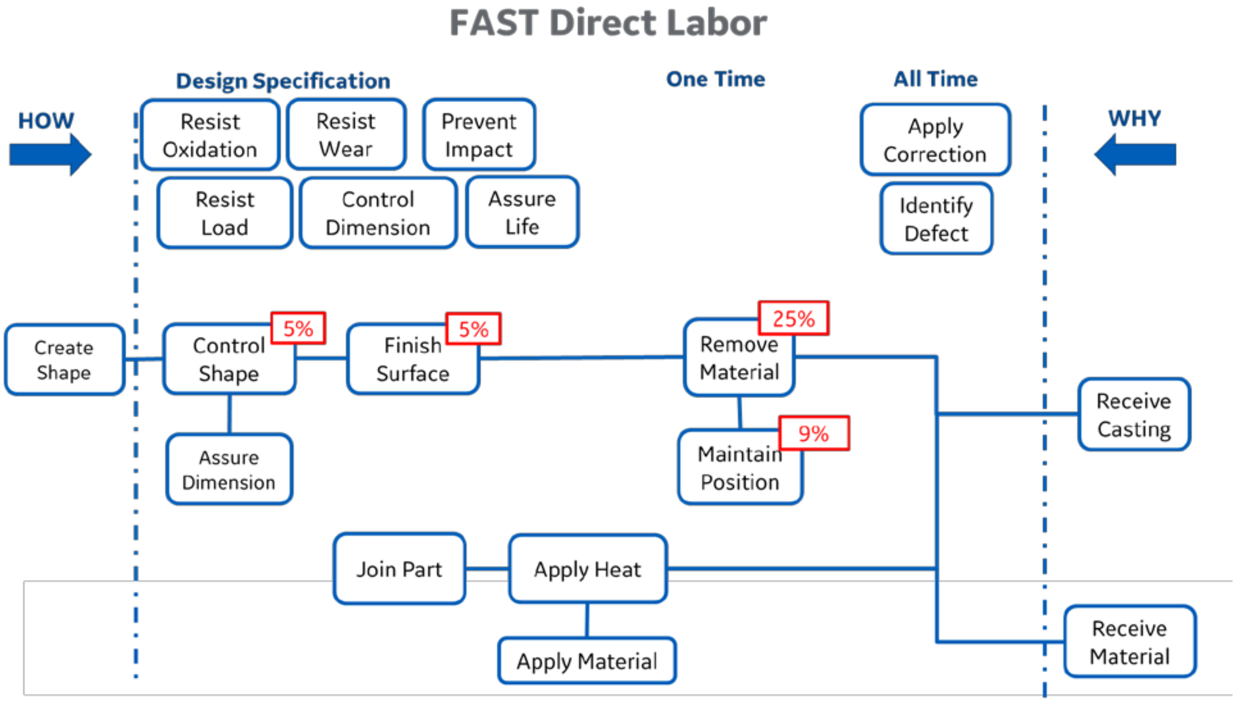


Figure 9 FAST DL for blades from investment casting technology - © Company, LLC - All rights reserved.

Four functions were chosen from DM FAST, while the remaining four were chosen from DL one (highlighted in red in the two fast diagrams). In this way, the product FAST diagram was coupled with the process FAST diagram, thinking to the overall functionality of the blades module (for example including the contributions from engineering and sourcing teams). After completing step 2.2 following the upgraded version of the VAVE methodology, the process continued with the Creative Phase (Step 2.3) focusing on ranked functions identified and to the other steps 2.4 and 2.5 as per standard methodology. The design team evaluated and validated the applicability of the parametric costing curves for the new design after applying the VAVE stream. The new design consists of a geometrical optimization of the existing design (material selection has been updated), as well as the possibility to avoid a few steps of the manufacturing process (i.e., the coating process). Considering these design changes, the proper raw material costing curve was used for raw material while, for machining, the same curves reported in Table 4 were applied.

5.1. Main results of the new blades design

A consistent gap (approximately 30%) between the original cost estimate and the target cost was observed at the beginning of the project. The gap dropped down from around 30% to 5% after using the VAVE methodology, resulting in a cost reduction of -25% when compared to the original design. Figure 10 shows the impact of this methodology on the overall cost of each function associated with each item studied when applied to gas turbine blades. In particular, a cost breakdown by function is presented, showing which function is worth prioritizing for new idea generation. It is worth noting that four of the top eight cost contributors are from the DM FAST diagram for turbine blades (*Prevent Leakage, Resist Temperature, Guide Flow and Resist Pressure*). On the other hand, two contributions come from the DL FAST diagram, with *Remove Material* having the most impact, accounting for 25% of the overall blade cost. Approximately 70% of the overall cost is handled using design to cost ideas by analyzing these six functions (green bars in Figure 10) and creating ideas and proposals based on them. This distribution of cost breakdown by functions made a crucial role to guide idea generation (Step 2.3) and the subsequent evaluation (Step 2.4 and 2.5). After the creativity phase (Step 2.3), where about one thousand ideas were generated, the value engineer led the design team to filter them in order to remove more remote ideas, find duplicates, and then classify the most promising ones (Step 2.4). Following this screening, the design team initiated building some solid proposals, applying their engineering judgment and expertise to estimate cost-saving, benefits, drawbacks, etc. (Step 2.5). After completing the implementation of approved ideas, the total cost of blades has been lowered by 25%.

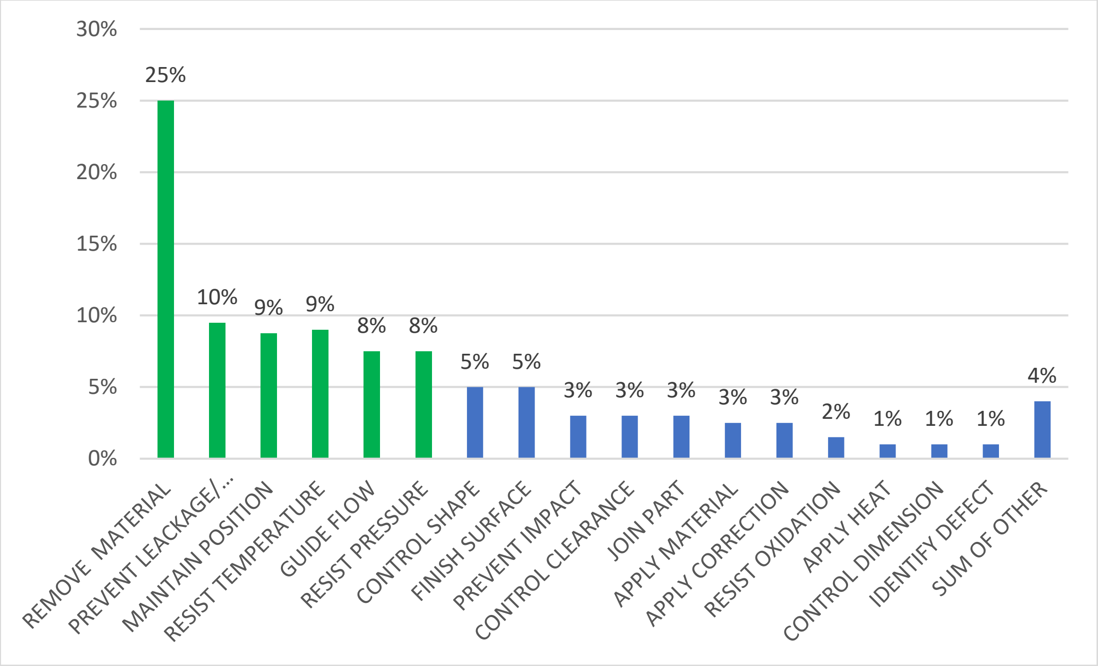


Figure 10 Current Cost Breakdown by Functions - © Company, LLC - All rights reserved.

As a result, 20 proposals with the first design estimation of saving have been reported. For all proposals Technical Impact/Risk, Commercial Risk and Saving Confidence were evaluated.

5.2. Comparison between old and new design for the blades

Several changes were made to the geometry of the blades in comparison to the original design. These geometrical changes were possible due to the alternative material selection (i.e., raw material) and the definition of a new set of manufacturing processes (i.e., the adoption of a novel coating type or coating elimination, change in heat treatment requirements, etc.). Without following the proposed methodology (considering both streams), the design team could not have the possibility to identify a high number of redesign and process proposals to reach the target cost. The main proposed design solutions are summarized in Figure 11. For the sake of confidentiality, no more details can be reported in this work (i.e., the type of material adopted, the new blade's geometry, the type of the coating process, etc.).

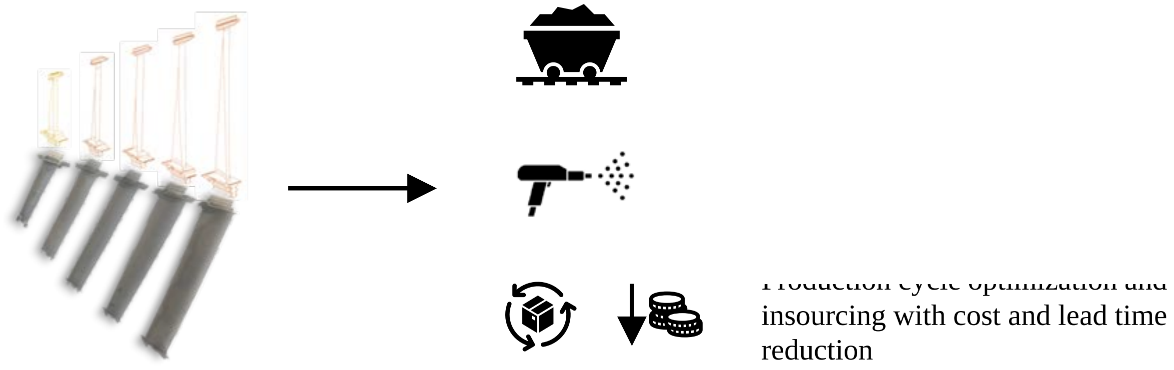


Figure 11 Updates in proposed design - © Company, LLC - All rights reserved.

Referring to CER and considering that the design team acted only on product cost as per option b of Table 3, having maintained the same design requirement satisfaction, the product value of the new design has been assessed:

$$Requirements\ Satisfaction_{afterVAVE} = Requirements\ Satisfaction_{beforeVAVE} \tag{3}$$

$$\frac{ProductValue_{after\ VAVE}}{Product\ Value_{before\ VAVE}} = \frac{\frac{Requirements\ Satisfaction_{afterVAVE}}{Product\ Cost_{afterVAVE}}}{\frac{Requirements\ Satisfaction_{beforeVAVE}}{Product\ Cost_{beforeVAVE}}} = \frac{\frac{Estimated\ Cost_{before\ VAVE}}{Target}}{\frac{Estimated\ Cost_{after\ VAVE}}{Target}} \tag{4}$$

$$ProductValue_{after\ VAVE} = \frac{Estimated\ Cost_{before\ VAVE}}{Estimated\ Cost_{after\ VAVE}} \cdot Product\ Value_{before\ VAVE} \tag{5}$$

$$\begin{aligned} ProductValue_{after\ VAVE} &= \frac{Estimated\ Cost_{before\ VAVE}}{0.75 \cdot Estimated\ Cost_{before\ VAVE}} \cdot Product\ Value_{before\ VAVE} = \\ &= 1.33 \cdot Product\ Value_{before\ VAVE} \end{aligned} \tag{6}$$

Considering that cost has been lowered by 25% by applying VAVE techniques, new product value increased by 33% thanks to the VAVE methodology application.

6. Conclusions

Design to cost is a key activity that must be included in every project plan. To raise the overall value of a product, a trade-off between product cost and functions is needed, particularly for gas turbines, which are complex products with thousands of parts and are subjected to very stringent requirements. Value engineer tries to keep the product cost model updated, during each product development stage, highlighting the gap between target and current cost estimation. Depending on the complexity and risk of the proposal, the program leadership team shall set a proper level of approval for design changes (internally or at the configuration board, where the whole technical and strategic leadership is involved). Value engineers can expand the design space and undertake extensive analysis on both material procurement and the subsequent machining process using the novel approach outlined in this study. The example presented in the case study regards the gas turbine blades, and it allows to demonstrate the worth of this approach. About 20 proposals were generated and evaluated, reaching a cost savings of approximately 25%. The time required to conduct all the process steps, and in particular the VAVE approach, is the main limitation of the proposed approach. On the other hand, having two different Step 2.1 and Step 2.2, one dedicated to DM and another to DL, constitutes a novelty and a strong advantage of the proposed method. Automatic functions for FAST diagrams generation for both standard components and processes would be very useful in overcoming this bottleneck and shortening Steps 2.1 and 2.2. Conceptual costing may be used to evaluate different architecture scenarios taking into account impact on cost, with the help of automated tools and models, starting from preliminary stages. The case study presented in this work for gas turbine blades clearly underlines that this method is a cardinal achievement for early cost estimation. Data collection and use for the parametric cost curve definition is another cornerstone of the method which is time-consuming and requires continuous update.

The next step in cost evaluation and optimization is the possibility to increase the level of collaboration with suppliers: knowledge formalization and sharing are crucial to lowering the product cost avoiding risks and uncertainties on the cost estimation. A co-design environment with suppliers might take advantage of developing an automated costing tool and a database of knowledge that includes all previous project design practices and experiences.

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