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PRODUCT FAMILIES: A COST ESTIMATION TOOL TO SUPPORT *"THE CONFIGURATION OF SOLUTION"* PHASE

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Abstract

The definition of methodologies to support the development of product families is a challenging problem which has received much attention, as can be seen in the literature referenced. In this context, *the configuration of solution* phase is a basic task. When a company studies a new product variant it is important to evaluate, early in the process, different alternatives. The product cost can be among one of the most meaningful criteria used to determine an optimal solution. Therefore, it is advantageous to be able to estimate the cost in the design phase, where the larger part of it is committed. This work shows how a cost estimation method can be used effectively within a framework, to manage the configuration of a product variant. In more detail we describe a low-cost prototypal software system which allows the configuration of the solution and the determination of production costs related. Additionally a practical example is shown, which documents results of collaborative efforts with an industrial partner, who is a manufacturer of woodworking machines for the wood panels polishing (calibrating/sanding). To optimise results while at same time complying to the company's needs, the cost estimation tool implemented has been used in the machining operations domain.

Keywords: modularity, product configuration, cost estimation, feature-based CAD model

1 Introduction

The current economic trend forces companies to produce low-cost and high quality products in order to maintain their competitiveness at the highest possible level. In this context, the major challenge for companies is to offer a wide range of products to attract different new potential consumers and at the same time respond quickly to dynamic customer needs. This means facing wide and rapid product variations with an increasing complexity of the product design process. The product development methodologies based on the paradigm of "*mass customisation*" can be a suitable approach to produce items that best serve the specific customer needs while maintaining the mass production efficiency. In fact, if variety can imply a relevant increase of production costs, the use of product platforms and related product families can have three different advantages: short time to market, high variety, economies of scale [1].

The essence of "*mass customisation*" lies in the ability of the product developers to perceive latent market niches to carry out technical capabilities and therefore to meet the diverse needs of target customers. To support customised product differentiation, paying attention to avoid an excessive proliferation of parts, a product family platform is required to characterise customer needs and subsequently to fulfil the specific needs by configuring and modifying well-established modules and components. Such process of product variant definition has been called *configuration of solution* [2]. In this phase, the design team configures/assembles the module instances, adding or deleting optional modules, to achieve the best functional solution. But, from an economic perspective, if on the one hand, the satisfaction of individual customer needs can be of great value to customers, the company, on the other hand, has to justify the specific investments for a low production volume. An effective means of making this decision is to use a cost estimation system in the design/configuration phase. In fact, it is known that over 70%-80 % of the production cost of a product is determined during the design phase. Thus, thanks to the cost estimation, designers can study many design alternatives and the management has an early indication of the product cost and, therefore, is able to make strategic decisions. In this scenario, the goals of the present work are set as follows. In order to support the design team in the decisional process, it is necessary to develop a methodology to estimate the product cost in the variant definition phase. The method can be based on the modular structure of the product and can be integrated within a module configuration tool. In this way, the team can rapidly perform the evaluation of different solutions. The further aim of our work is to test the adoption of such methodologies in small and medium sized enterprises, hence, the framework has to be implemented in a suitable system in terms of cost and performance.

2 Related work

For years many companies have been studying the modularity and the possibility of the application of product platform concepts in their production [3], [4]. It is known that product families based on a product platform have been successfully developed within different industries (automotive, consumer electronics, aerospace, office furniture). In literature [4], [5] various methodological approaches are described, however, very often they are applied within big companies (for example Volkswagen or Black&Decker, as cited in [5]). But similar problems are emerging also in small and medium sized enterprises (SMEs). Nowadays, SMEs sell their product lines in the global marketplace and they must beat the concurrency of big enterprises. They must be more flexible (high quality customised products in a shorter time) than competitors. It can cause, as consequence, a meaningful increase of the product development cost. In this context, a desirable approach to product development process, also for SMEs, is a concurrent one with an emphasis on cost control.

Studies have shown that the greatest potential for cost reduction is at the early design phase, where as much as 70%-80% of the cost of the product is decided [6]. The Design for Cost methodologies have been studied and formalised since 1985 [7]. The problem can be resumed in the following way: developing a system allowing the designer to calculate costs in the design phase managing the knowledge of the production processes and, hence, the costs incurred therein [8]. Many CAPP systems have been developed during the last years but they are too complex to be used in the design phase because they require a lot of information beyond the product characteristics. In contrast, the designer, to compare the alternatives, needs a simpler tool which estimates the design solution costs only on the basis of product geometry and some additional design information.

A large number of approaches and methods for cost estimation have been presented. An interesting classification has been reported in [9]. According to [10] cost estimation can be divided into two basic methodologies: generative cost estimation and variant based cost estimation. In the first case, the estimate is based on a decomposition of the costs related to the expected production processes. In the second case, the analysis of the similar past products allows the evaluation of new ones. We believe that a suitable cost estimation tool should include a combination of these two approaches. Feature-based costing [11] can be considered an optimal compromise between them. In fact, features can be used to describe the geometric information of products at different levels of detail, and they can be used to collect all functional and technological information (tolerances, surface finishing, manufacturing cycle, etc.) further needed. Yet, features defined in a previous product can be reused for the new solutions inheriting all process information. Parametric feature-based 3D CAD modelling systems can furnish the practical support to manage the cost information along with the functional product definition and its virtual representation. Several feature-based costing technology applications are reported in scientific literature (an overview of recent works is provided in [12]). For example, in [13] an interesting system for estimating costs of sheet metal components is described. However, there exists no satisfactory computer-aided support for the cost estimation task in the machining operations domain. Important research works have been carried out [14], [15], but, in our opinion, the systems developed are not well-integrated in the design process flow. Due to these aforementioned problems, we do hope our contribution in form of a framework developed along with studies and practical experiments related to the integration of product design with cost estimation regarding configurable products helps to fill in some gaps in system and tool development still missing.

3 The *configuration of solution* problem

A product can be defined configurable if, on the basis of the market requirements, it is possible to accomplish a rapid and low-cost design modification that fully satisfies given customer specifications. From a practical perspective, the configuration of product variants should be handled with tools that simultaneously manage the design knowledge base (design rules, functional constraints, etc.) derived from the *design for configuration* process, and the geometrical model of the product. In Figure 1 are illustrated the product structure and the corresponding design variations to obtain a product family member.

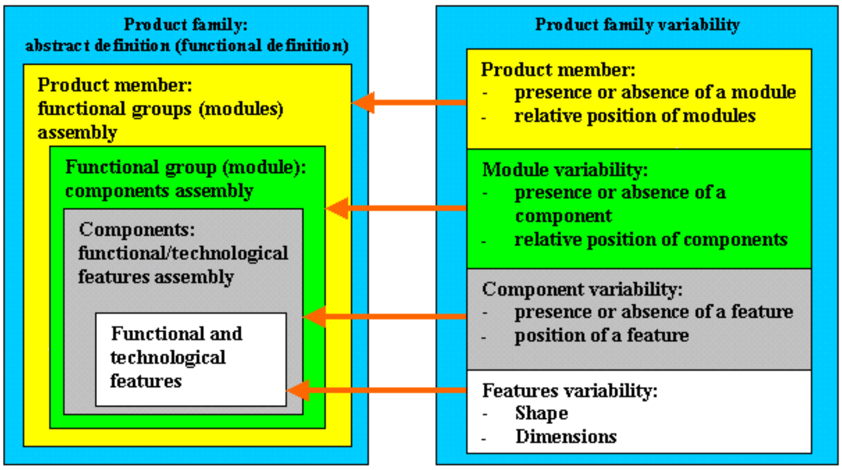


Figure 1. Configurable product structure definition (left) and the related variations (right).

Obviously, customer requirements could be satisfied with several different alternative solutions. The goal here is to automate the configuration phase to allow the designer to analyse several possibilities in a short time [16], [17], [18]. In such practical software applications the developed design support systems can automatically manage the dimensional variability at all levels (features, components, modules and assembly), on the basis of design rules implemented. Furthermore, it is possible to manage the presence or absence of features, components and modules. The modules, for example, can be stored in a library (modules database) from which the designer can retrieve instances based on specific functional requirements. Problems in rule definition to obtain a single multilevel structure representing the platform to configure automatically the alternative assemblies (product layouts) still pose some limitations. Therefore user interaction providing designer experience is still necessary. In this context, our present objective is the extension of these product variant configuration tools ([17] and [18]) with a system to predict the product cost.

4 Approach and system description

The basic idea of the approach, as outlined below, is to provide a flexible, inexpensive and easy to use framework for the configuration and the economic evaluation of modules to support the definition of a new product (product variant) within a product family. Basically, we focus our attention on the cost estimation methodology and the related developed tool.

4.1 Outline

Cost estimating strategies are based on the determination of driving cost product characteristics that are called *cost drivers*. According to Weustink [10], for a mechanical product, they are related to: product geometry, material, manufacturing processes (surface finishing, tolerances, assemblability, etc.) and production planning (resources management). While the structure of a modular/configurable product is defined, costs can be directly related to modules. Ideally, every module could be predefined as a collection of commercial standard components and manufactured components known. In this way the value of cost drivers could be easily determined. The product cost calculation could be estimated as a sum of the cost of modules used and the assembly cost. But this scenario represents a short-sighted approach to the product configuration. As outlined earlier, the main problem of the *configuration of solution* task is the management of modifications to satisfy the specific customer requirements (market niches). As a consequence the designer needs to configure not only pre-existing modules but needs to modify the characteristics within the modules themselves, i.e. varying components dimensions or varying the components way of assembly. An effective product configuration system should be able to manage the design knowledge to assembly the standard modules but, mainly, to allow the non standard modifications. The cost estimation system has to be based on the same principle. When the designer configures a non standard solution, the cost estimation system has to be able to extract the design parameters for determining the cost drivers values to evaluate the product cost. We assume that for addressing a correct cost estimation it is necessary to analyse a detailed product model. For cost evaluation purposes it is assumed that the product variant configuration can be performed managing two change typologies. They are classified in: modules *internal changes* and modules *external changes*. When we modify internally a module, i.e. substituting a component with another (Figure 2 upper part), the neighbouring modules are not influenced and the cost variation can be estimated analysing only features specific for this module. For external changes we intend new requirements implying the variation of module interfaces or module boundaries (Figure 2 lower part). In this case it is necessary to determine all modules involved and to evaluate the cost of their new configurations. For the internal changes, usually, it is simple to realise a detailed module model (module instance), hence it is possible to study many alternatives. The modules external changes are complex and the detailed configuration process is time consuming (also with dedicated configuration tools), as consequence it is difficult to compare more than two solutions. Then the cost estimation method has been based on a two-level approach. If the product variant implies a module external change, before carrying out the configuration task it is necessary to execute a qualitative estimation between the design alternatives considering the modifications impact on the entire assembly (for example: the number of modules involved/modified, the number of interfaces to be modified, etc). The result is the elimination of many alternatives.

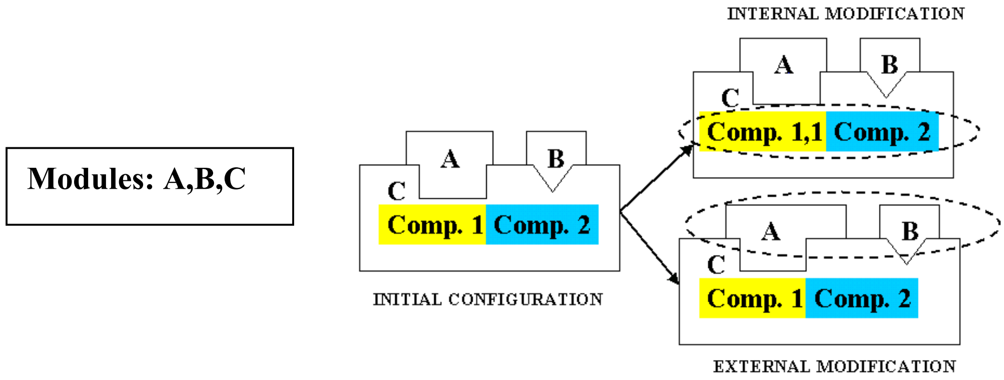


Figure 2. Classification of modules changes: internal and external.

At the second level, using detailed models, a quantitative approach, both for the accepted solutions regarding the external changes and for internal changes, has to be adopted.

The qualitative evaluation can be supported using tools similar to Change Propagation Methods (CPM) [19], where the matrix represents the product family connections. The rows and columns can represent the functional modules and the matrix values are indexes of the correlation between modules. If a direct interface between modules is present, also an interface cost is reported in the matrix. When an external change is required, the design team determines the possible solutions and evaluates them on the basis of a modification impact coefficient being calculated using the matrix values. We neglect a wide description of this phase to focus our work on the quantitative approach developed.

4.2 The cost estimation tool: characteristics and system framework

For a configurable product, as outlined earlier we can consider a product variant as a collection of standard modules and customised modules (Figure 3).

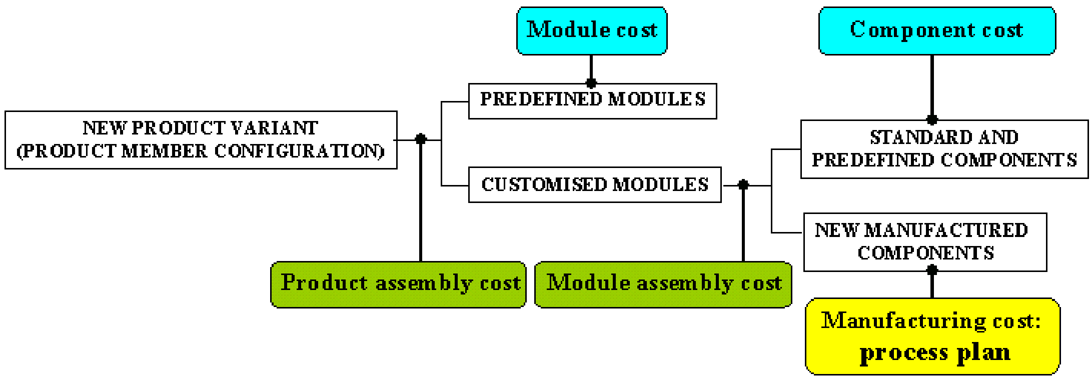


Figure 3. Product structure oriented towards cost attribution.

These last modules can be an assembly of standard/predefined components and new components. The product manufacturing cost is given by the sum of the assembly costs, of the manufacturing costs of components and of standards objects costs (all coloured boxes). The costs of previously used (or standards) components/modules (blue boxes) are known and they can be already stored in the databases as attributes. On the other hand, the assembly costs terms (green boxes) and the new components manufacturing costs (yellow box), have to be calculated for every variant.

In the developed systems, details of the product variant definition process can be found in earlier publications [17], [18], the configuration tool generates a specific product hierarchical structure. Such structure is similar to a multilevel bill of materials where attributes (i.e. code, material, dimensions, price etc.) determined during the configuration phase are encapsulated within the objects definitions. The systems creates also a detailed 3D CAD model (assembly, sub-assemblies and parts). The cost estimation system retrieves and navigates the product structure to identify the standard modules and their cost attributes, and the customised modules. For the latter the 3D CAD models are automatically extracted to analyse the changes influencing a cost modification. The system framework is reported in Figure 4.

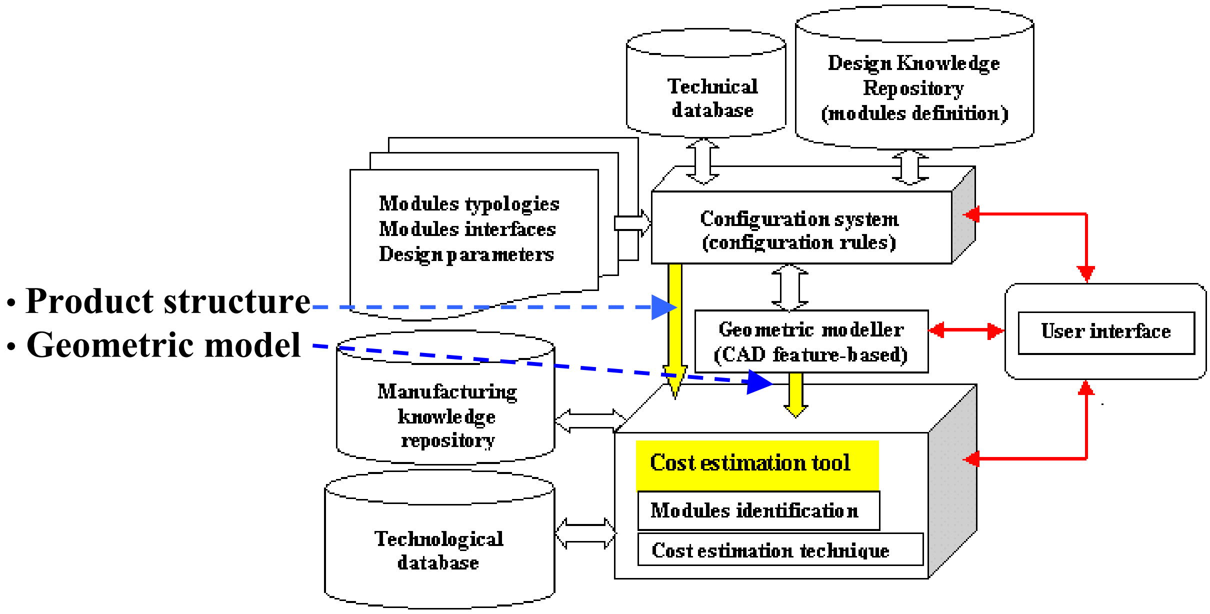


Figure 4. System framework.

Up to now, we have concentrated our research on the features level and on the component level. We are going to approach the assembly level (both for the module and for the entire product). We would determine an index characterising the complexity of way of assembly, such index should be proportional to the cost related to assembly constraints defined within the CAD model. Currently, the system estimates the assembly cost on the basis of number of assembly operations, determined through the analysis of the assembly constraints used within the CAD model.

Returning to the component cost a feature-based costing approach has been considered. In the manufacturing knowledge base we collect the company manufacturing rules and the process planning rules. Currently the resources and production planning rules are neglected because in SMEs they can be easily monitored. The technological database contains information on materials, tools, machines, etc. and related costs (being determined by using specific company experience). On the other hand, we have a 3D CAD model in which geometry, material, tolerances, accuracy etc., can be defined. In particular, we can use a parametric feature-based CAD system in which the product structure can be viewed in terms of features, components and assemblies, that are meaningful aggregation levels also for the cost drivers attribution. From all these elements information can be directly extracted (dimensions, shapes, volumes, weights, assembly rules, etc.). Also many properties (material, surface finishing, machining cycle typology, etc.) can be added in the design phase interacting with the CAD data structure, or automatically, the information can be stored within the technical database, or interactively, specifying attributes on model faces and features. Matching a company's manufacturing knowledge and the features model a process plan for the components can be automatically obtained. Within the implemented software application the user can interactively modify the generated process plan. In the process plan is collected all information regarding the manufacturing and control phases and also the resources required. Hence, it is possible to perform the component cost calculation analysing the process plan determined. The total product variant cost is determined aggregating the various terms calculated.

For the framework as outlined, a system has been implemented for product configuration and product cost modelling. The proposed solution contains a parametric feature-based CAD system (Solid Edge by Unigraphics), a user interface (developed with Visual Basic and Microsoft Excel) and a knowledge base (Microsoft Access) to manage the company manufacturing information (machines, tools, cutting parameters, manufacturing cycle typologies, fixtures). The cost estimation system core has been implemented using Visual Basic in order to comply with requirements regarding applications in a SME industry, inexpensive, easy to handle commercially available software was chosen. The system communicates with the geometry engine through APIs to obtain geometric, topological and assembly features (constraints) required for process planning of manufactured components. It retrieves also he product variant structure to identify standard modules and components and extracts information on related costs. Currently, the developed tool, manages machining operations such as 2,5-axis milling, turning, drilling, tapping, boring, grinding and, in part, 3-axis milling, for steel and aluminium alloys. Analysis of knowledge formation of additional manufacturing technologies to be included in the system is currently underway.

5 Practical application

The tool is currently under test in collaboration with a small industry (Viet S.P.A., www.viet.it), that develops woodworking machines for polishing of wood panels (calibrating/sanding). The company manufactures standard product lines and systems on the basis of specific customer requirements (production to specification). The past production has been analysed and it has been chosen as a test the application of the modularity rules and the automatic module configuration tools. But they need also, in the early design phases, a realistic prediction of system cost to present the possible solutions to the customer. Their systems are essentially composed of commercial components and of machined components (usually manufactured by milling and turning). Thus, the application of the cost estimation system developed can give to the design team the product cost prediction in a very rapid way.

To illustrate the results we report an example of the change order (ECO) process within the company of our industrial partner. A customer requires a new calibrating/sanding machine with a larger diameter of calibrating rollers. The engineering department identifies the machine most similar within the line of standard products. The required modification concerns specifically the calibrating rollers module but it propagates the effects on other modules (i.e. the machine frame). Hence the design team studies the different alternatives and establishes several product variants, all of them functionally valid. Through a qualitative cost analysis they reduce the number of solutions. The next step is the realisation of detailed virtual models. The configuration system can be used to accomplish it. Two different product variants are defined. In Figure 5 the alternatives for the panels calibrating module are shown.

In these two last situations we have: different number of components, different standard components typologies, different machined components and different assembly strategies. The cost estimation system analyses the structures of modules and the related CAD models (assembly and parts). When the design system configures the product models, some attributes (i.e. cost for a standard component, materials) are automatically connected to the objects. Further meaningful information for costing is defined automatically within the CAD model (i.e. geometry/features, assembly rules and constraints).

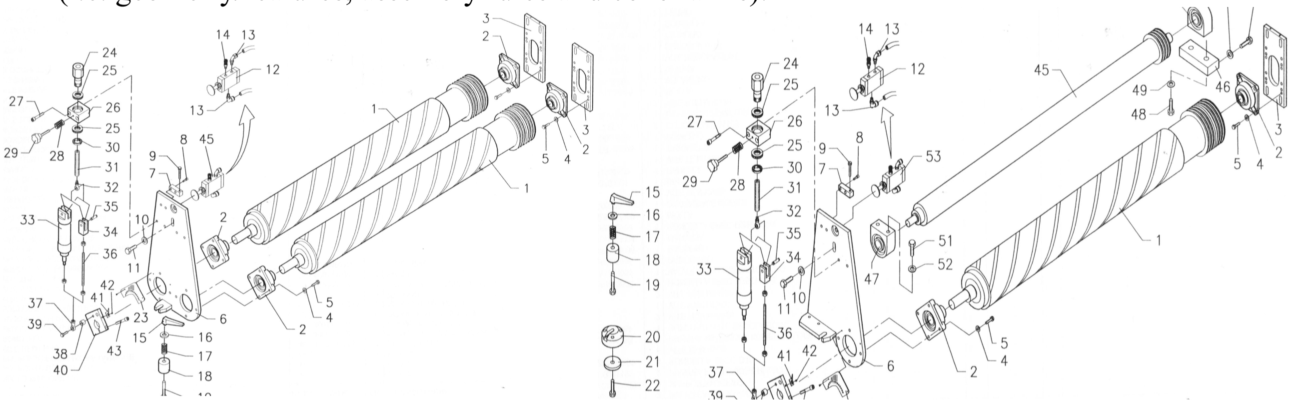
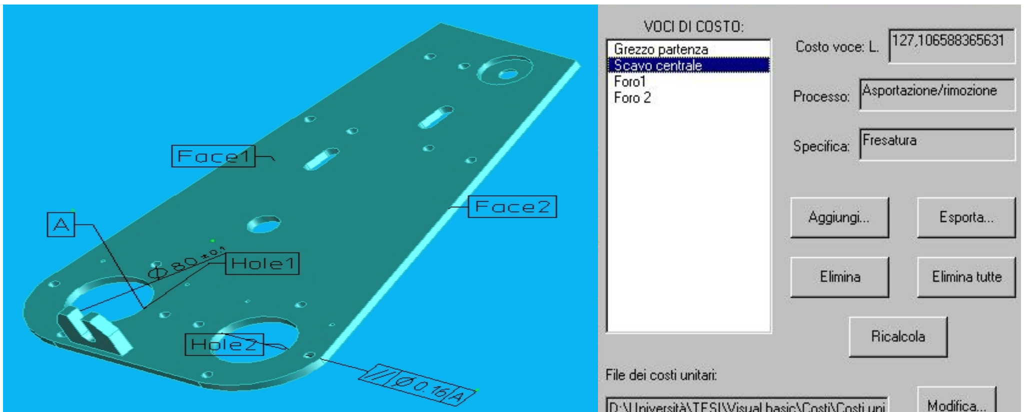


Figure 5. Two module variants for the panel calibrating function.

Additional design information (surface finishing, dimensional and geometric tolerances) needs to be interactively provided to perform the estimation of manufacturing cost for the machined components.



1	COMPONENT MANUFACTURING COST ESTIMATION REPORT						
2	PART_6. SUPPORT_PLATE (MATERIAL_Fe 430)						
3	Feature	Operation	Machine	Tool	Fixture	Time (s)	Cost
4	Face2_part_6	Contour Milling	DM 1320	T0103	F 1320-101	32	****
5	Face1_part_6	Rough Milling	DM 1320	T0001	F 1320-103	56	****
6	Face1_part_6	End Milling	DM 1320	T0006	F 1320-103	40	****
7	Hole2_part_6	Milling	DM 1320	T004	F 1320-103	16	****
8	....						
9	Hole7_part_6	Drilling	RS 115	T01	F115_01	8	****
10	Hole8_part_6	Drilling	RS 115	T02	F115_01	8	****
11	.....						
12	Hole2_part_6	Diameter Dimensional Control			G 211	54	****
13	.....						
14	Axis_hole1_part_6_Axis_hole2_part6	Orientation control (parallelism)			GS 101	206	****
15	.....						
16	Number of part repositioning	8					****

Manufacturing Cycle / Unit Cost per Operation / Tools Typologies /

Figure 6. User interface in the process plan interactive definition (upper), output report (lower).

Elaborating and organising such inputs and using the manufacturing knowledge implemented, the cost estimation system can evaluate the assembly cost and the manufacturing cost. In the figure below it is shown a part of the total cost report (Excel spreadsheet, where dotted lines represent the omitted machining operations) for the component number 6 of the module illustrated in Figure 5 (left). Our partner considers costs as confidential data (asterisks in the table). Additionally, if the user considers some operations not properly assigned to the features, an interactive commands window is provided to modify the calculated plan. Several manufacturing operations are defined, the user selects the most appropriate operation and, navigating the feature model, associates it to a feature (or a group of features). The system recalculate immediately the plan and the cost related. A similar report is produced for the entire product variant. The report is structured to highlight the different cost values, hence it can be a suggestion to the design team for adopting cost control strategies.

6 Conclusions

A method for estimating production costs in the configurable products domain has been presented. The method has been thought to be used within a product variant configuration software tool. The cost estimation has been put in relation with the product variability. Hence, the approach has been based on a two-level structure (qualitative and quantitative) to manage the module external changes and the module internal changes. The quantitative evaluation of different design alternatives is accomplished using a feature-based approach. The presented methodology offers several advantages for the user. First of all, it allows to analyse many product variants considering a strategic parameter such as production cost, it enables also designers to manage the manufacturing rules and it warns them for costly errors. Second, the system is completely adapted to the know-how of the company. Features can encapsulate the cost knowledge supporting the modularity and the reuse of information. The knowledge stored is entirely dynamic and may easily evolve including other methods. Third, the system is integrated with low-cost design tools used in the engineering department. To fully reach the research objectives, and according to the promising results, the system should be extended to consider/integrate more manufacturing processes such as sheet metal processes. Currently we are also working on the optimisation of the entire configuration system to manage product assemblies.

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