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Design for Manufacturing and Assembly vs. Design to Cost: toward a multi-objective approach for decision-making strategies during conceptual design of complex products

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Abstract

Design-for-Assembly (DfA) and Conceptual DfA criteria are used in the generation of cost-effective assembly sequences for complex products. The design freedom suggests optimal solutions in the assembly time minimization problem regardless costs and issues about materials and manufacturing processes selection. The goal of this approach is to investigate how the application of the conceptual DfA affects the material and manufacturing costs (Design-to-Cost). A complex product (tool-holder carousel of a CNC machine) is used as a case study. The outcome is an approach to support designers and engineers in the re-design process for the product development and cost reduction.

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Keywords: Conceptual Design for Assembly, Design to Cost, Manufacturability, tool-holder carousel

1. Introduction

Different Design-for-*X* (Df*X*) methods have been developed in recent years to aid designers during the design process and in the product engineering stage. Methods for efficient Design-for-Assembly (DfA) are well-known techniques and widely used throughout many large industries. DfA can support the reduction of product manufacturing costs and it provides much greater benefits than a simply reduction in assembly time [1]. The DfA techniques have been developed since the early 1980's and the most famous is the Boothroyd and Dewhurst method (B&D) which is widely accepted and used. The B&D method measures the complexity of assembly so producing a quantitative result [2]. However, this method is rather laborious and in most cases, it requires a detailed product design or an existing product/prototype. Other approach investigates the product assemblability starting from the product functional structure [3]. In this way, the DfA technique can be applied during the conceptual design phase when decisions greatly affect production costs. Its main scope is to minimize the assembly time and costs by reducing components without using detailed product models. Even so, the conceptual DfA, as the authors call their method, do not consider manufacturability aspects such as the material selection or the most appropriate process to build up components and parts. Furthermore, product design and optimization is a multi-objective activity and not only limited to the assembly aspects.

In this context, this paper proposes an improvement to overcome the above-mentioned weak points and to optimize the product assemblability as well as the parts manufacturability by taking into account the best cost-effective technical solutions. The step beyond the current state of the art is the possibility to optimize both assembly and manufacturing within a cost-driven approach able to roughly evaluate the cost of the manufacturing process in the early design stage when the product model is not yet available and defined. The main goal of this work is to define a multi-objective design approach which aims to have a comprehensive analysis of the manufacturing aspects (including assembly, materials, processes, costs and times). This is particularly important to avoid design solutions which can be excellent from the assembly point of view but not cost-efficient in terms of manufacturing costs and investments.

In the following sections, the proposed approach is reported in detail after a brief review of the research background. In order to show the approach and its application a case study has

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been analysed. A complex sub-assembly of a machine tool (tool-holder carousel) has been re-designed and the results compared with previous design solutions in terms of overall costs, assembly time and number of components.

2. State of the art and research background

The design stage is a long and iterative process for the development of certain products. Design stage activities can be divided into four main phases: (i) Problem definition and customer needs analysis, (ii) Conceptual design, (iii) Embodiment design, and (iv) Detail design. In the first phase, customer requirements are collected and analysed, then, the requirements are translated into product functions and features, and finally, concepts that can satisfy the requirements are generated and modelled [4]. It is well-known that, although design costs consume approx. 10% of the total budget for a new project, typically 80% of manufacturing costs are determined by the design of the product [5] [6].

The manufacturing/assembly costs are decided during the design stage because its definition tends to affect the selection of materials, machine tools and human resources that are being used in the production process [7].

DfA is a methodology which gives the designer a thought process and guidance so that the product may be developed in a way which favours the assembly process [8]. DfA has been translated in numerous operative tools in order to simplify product design and to support designers in making design decisions. DfA proposes a systematic procedure to maximize the use of the same components and to identify the main problematic solutions in terms of assembly time.

DfA can be strongly advantageous if used during the first phases of conceptual product design since it can improve the manufacturing process and have a deep influence on product costs [9]. However, traditional DfA methods are related to the detailed design phase when much of the design process has been deployed and solutions have been identified [10]. The Boothroyd and Dewhurst method (B&D) is one of the most diffused DfA approach in the industrial practice. The method is based on the analysis of the product assemblability through the calculation of a numerical index [2]. Different design solutions can be compared by evaluating the elimination or combination of parts in the assembly and the time to execute the assembly operations. The approach is strictly correlated to the number of components and to the manual operations needed for system assembly. This estimation can only be calculated when it is possible to use a detailed design or a physical product model [11]. During the conceptual design phase, when the most important product decisions are made, such data are not present so the method cannot be applied. This is the only drawback of this powerful approach.

Stone et al. [3] propose a possible solution. They define a conceptual DfA method in order to support designers during the early stages of the design process. The approach uses two concepts: the functional basis and the module heuristics approach [12]. The functional basis is used to derive a functional model of a product in a standard formalism and the module heuristics are applied to the functional model to identify a modular product architecture [13]. The functional basis is obtained by using the classical Pahl and Beitz theory, where a *black box* represents the main product function and the flows of material, energy and signal are transformed by the *black box* itself [4]. The main function is divided into sub-functions and a complex tree structure is created. The lowest level of the structure is used to identify modules by adopting the cited heuristics [12].

Stone et al. [3] demonstrate that this method allows products with a high assemblability to be created, starting from the identified modular structure, and also allows solutions based on suggested modules to be designed. In this way, the resulting product has a minimum number of parts which can be inferior to the number determined by the B&D method. The approach has two weak points: (i) the identification of best manufacturing process for the part production and (ii) the related cost-efficient material.

The selection of the most appropriate manufacturing process is dependent on a large number of factors but the most important considerations are shape complexity and material properties [14]. According to [15], Design-for-Manufacturing (DfM) is defined as an approach for designing a product which: (i) the design is quickly transitioned into production, (ii) the product is manufactured at a minimum cost, (iii) the product is manufactured with a minimum effort in terms of processing and handling requirements, and (iv) the manufactured product attains its designed level of quality. DfM needs to take into consideration all the above and more factors in order to support decision making and provide this information in a timely and appropriate manner. Ultimately, most information can be reduced to a cost, the paramount driver to economical design. DfM converts most manufacturing information to cost indices, effectively normalising the disparate information and making possible direct comparisons [16].

DfA and DfM hardly integrate together, and the Design-for-Manufacturing-and-Assembly (DfMA) procedure can typically be broken down into two subsequent stages. Initially, DfA is conducted, leading to a simplification of the product structure and economic selection of materials and processes. After iterating the process, the best design concept is taken forward to DfM, leading to detailed design of the components for minimum manufacturing costs [17]. The procedure is cost driven and highly depends on the existing product design [18].

Cost estimation is concerned with the predication of costs related to a set of activities before they have actually been executed. Cost estimating or Design-to-Cost (DtC) approaches can be broadly classified as intuitive method, parametric techniques, variant-based models, and generative cost estimating models. However, the most accurate cost estimates are made using an iterative approach during the detail design phase [19]. Among the many methods for cost estimating, at the design stage, the most used are those ones based on knowledge, features, operations, weight, material, physical relationships and similarity laws [20]. To obtain an appropriate estimation of manufacturing cost, an initial process plan should be used. Initial process planning includes generation and selection of machining processes, their sequence, and their machining parameters [21]. To be efficient, DtC requires to be applied at the same time of DfM and DfA (conceptual design phase) in order to compare and make the design alternatives cost-efficient [22]. While the DfM and DtC is applied at the embodiment design or even worse in the detail design phase, this is only an optimization of an already selected design solution from the manufacturing/cost point of view. In this framework, the best solution adopted to minimize the assembly time and costs cannot be the best option from the point of view of manufacturing and costs.

3. Multi-objective conceptual design approach

In order to describe the proposed multi-objective design approach, some concepts need to be introduced. The first one is to set out the *product modules and properties* considering the functional basis and the module heuristics. Then, grounded on the concept of morphological matrix it is necessary to define feasible *design solutions*. Finally considering the *multi-objective approach* (DfA, DfM and DtC), suggestions for the product structure simplification and for the selection of economic materials and manufacturing processes are stated.

Fig. 1 shows the workflow of the proposed multi-objective design approach in relation to the traditional DfA approach. It is important to highlight that the proposed approach is able to consider different target design methodologies (DfX) early in the product design concept.

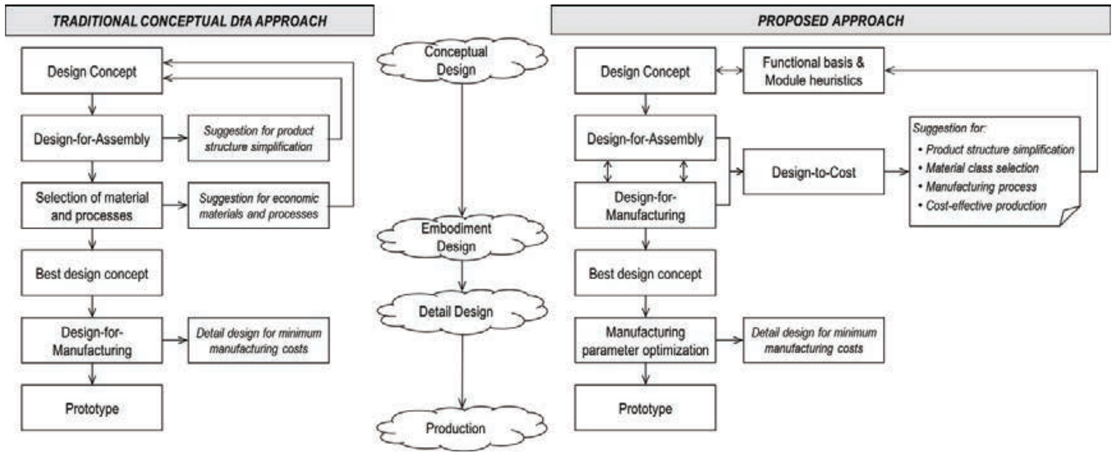

Fig. 1. Flow diagram and comparison between the *Traditional conceptual DfA approach* vs. the *Proposed approach*

3.1. Product modules and properties definition

Through functional analysis and module heuristic approach, it is possible to determine the number of functions which identify a product and the related flows (energy, material and signal). The functional analysis is able to break up the product in its constituent functions as a first step of design process.

The module heuristic identifies the in/out flows of each functions. By using this approach, it is possible to translate the product functions into functional modules. Furthermore, heuristics allow determining the specific properties of each functional module. A one-to-one mapping between product functions and modules is expected, but can be possible that several functions are developed only by one physical module.

3.2. Design solutions

The transition from product modules to potential design solutions (components or sub-assemblies) is based on the knowledge of specific properties identified during the generation of the *product modules*. A very helpful tool at this step is the morphological matrix which can improve the effectiveness of the conceptual analysis and translate functional modules to physical modules such as sub-assemblies or components. Designer skills, supplier and stakeholder surveys as well as well-structured and updated knowledge repositories can help in the definition of the design solutions suitable to implement the module under investigation and for the population of the morphological matrix. The morphological matrix can show an existing alternative solution for each functional module of a system and select the best one for a specific module.

Design solutions must be reliable and compliant with the properties defined in the module assessment.

3.3. Multi-objective approach

The multi-objective approach is the core of the proposed workflow and aim to balance different aspects of industrial production, such as assembly, materials and manufacturing processes taking into account the overall cost as a driver for the optimization design process. The multi-objective approach is following the product modules definition and the classification of design solutions, but it is still part of the conceptual design phase. In fact, in this phase are available only general information and not specific details about geometry, shape, manufacturing parameters, material designation, etc.

For example, the information available for the multi-objective approach are summarized as follow:

- estimated overall maximum dimensions (space);
- estimated overall weight;
- material class (i.e. Carbon Steel, Plastic, etc.);
- main manufacturing process (i.e. Machining, Casting, etc.);
- assembly operations (i.e. Manual/Auto, Welding, etc.);
- commercial/not-commercial (i.e. supplied or not);
- expected production rate.

These preliminary data are necessary for the multi-objective assessment. In particular, the alternative design solutions retrieved in the previous step are analysed based on rough cost estimation and based on designers/engineers knowledge. The concepts of DfA, DfM and DtC are applied at conceptual level to choose the best assembly configuration (best design concept) in terms of costs and productivity. This is an iterative process, as highlighted in Fig. 1, in which all the design solutions are evaluated in order to retrieve useful suggestions for the development of the product and its constituent components. The best design concept is not the best assembly concept optimized considering the minimum cost for the parts manufacturing, but the optimal solution in terms of costs, assembly, material and manufacturing process considering the production rate (batch) and all the other product features.

In the embodiment design phase, based on the conceptual design solution selected, different properties and parameters are defined such as the specific material (i.e. *Al wrought alloy EN-AW6005* from the *Aluminium alloy* class) or the specific manufacturing process (*High-Pressure Die-Casting* 1200 [ton] from the *Casting* processes). Furthermore, process parameter optimization (virtual model definition, manufacturing process parameters tuning, assembly lines arrangement, etc.) is pointed out in this step by the traditional design tools (CAD, FEM, etc.). Afterwards, the detailed design is defined and physical prototypes are realized before to start the production phase.

4. Case study: A tool-holder carousel of a CNC machine

A tool-holder carousel of a CNC machine tool for wood processing and machining has been analysed within this work as a case study. This system is responsible to feed the tool head with different tools for specific manufacturing operations (cutting, milling, drilling, contouring, etc.) The tool holder carousel is a complex assembly product as highlighted by the original design model proposed in Fig. 2.

Considering the functional analysis and the modular approach, several product modules have been identified in the conceptual design stage. The overall function of this complex system is "feed the CNC machine tools with specific tool". The functional analysis has general validity for this kind of product and can be repeated for other CNC machine models.

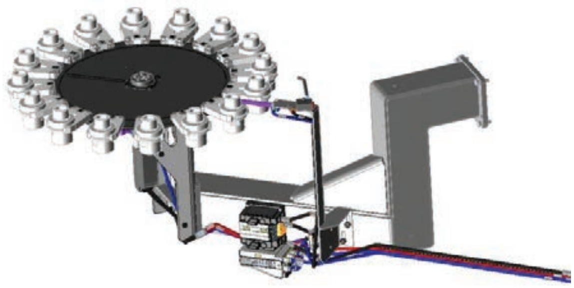

Fig. 2. CAD model of a tool-holder carousel of a CNC machine tool.

As example, two modules of this product are proposed:

- The carousel *Support*.
- The carousel *Grippers*.

Based on the proposed approach, different design solutions have been pointed out as design solutions. The different design solutions have been analysed following the multi-objective design guidelines.

A general overview of the implementation of the proposed approach to the selected case study is presented in Fig. 3. The figure pointed out different design solutions for the defined product modules and a rating for each aspect of production (Assembly, Material, Manufacturing and Cost) assessed by the different target design methodology.

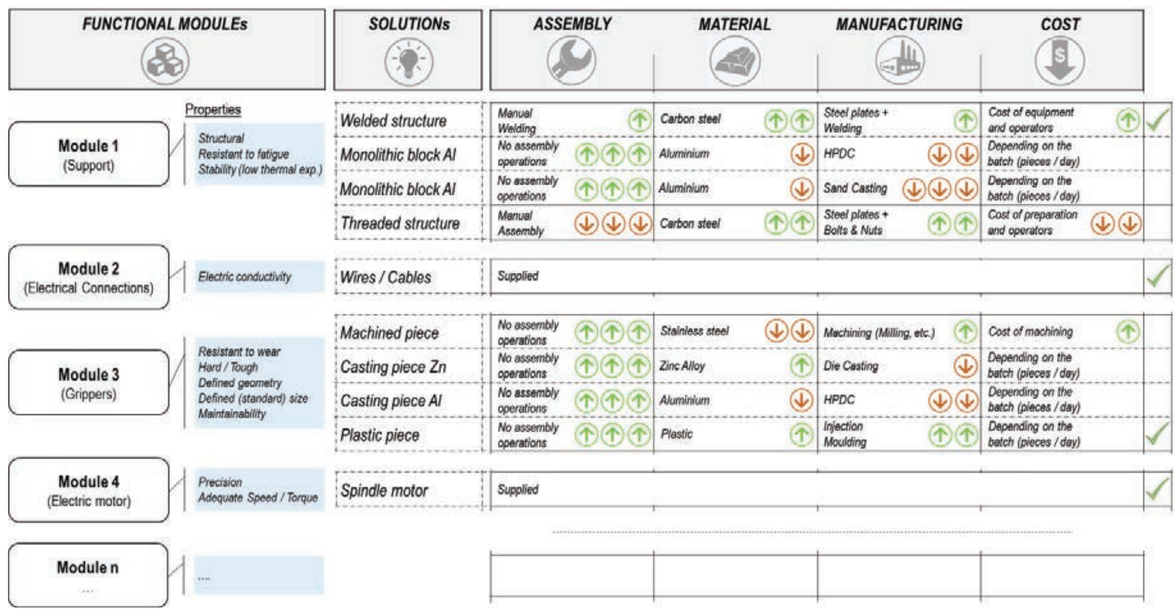

Fig. 3. Schematic representation of the proposed multi-objective design approach for the optimization of CNC machine tool-holder carousel example

Rough information have been assessed for the possible design solutions in order to define the rating scale (↑↑↑ - The best available solution; ↓↓↓ - The worst available solution) of each production aspect. For example, the current production rate has been roughly estimated at 1000 pieces in 5 year according to the average production rate of the platform of machine tool where the support will be used. Cost of materials, as well as cost of manufacturing processes have been retrieved by the assessment of the overall weight and dimension multiplied by the cost of each items. Furthermore, investment costs have been estimated based on the benchmarking analysis and suppliers' investigation for the different manufacturing processes considered. For the assembly, calculation of assembly complexity and time has been conducted based on this information and considering the knowledge and the expertise of the engineers involved in the design department of the company and internal interview of the assembly operators and Method Time Measurements (MTM) analysts. Several other different design solutions have been identified by the use of morphological matrix but they are not been reported in the figure because they are not feasible considering the requirements reported in the properties box.

The rating can be used as a simple graphic representation for the engineering consideration based on the costs analysis. As described above, the method is cost-driven and each solution has been investigated in terms of cost considering the defined production rate. Moreover, the rating has the purpose to create the basis for a mathematical model which can be used for future implementation of a numerical solver able to establish the optimal modules and their configurations.

Based on the proposed approach, it is important to note that, e.g., a new possible solution for the carousel support is a monolithic Aluminium block manufactured with HPDC (High-Pressure Die-Casting) process. This solution is the optimum in terms of time and assembly cost but considering the manufacturing costs, this is feasible only with a high production rate (higher than 1000) due to the initial investment of moulds, press and equipment. This is one of the most important results achieved considering the application of the proposed. The existing conceptual DfA approach does not consider manufacturing cost estimation and analysis in this early phase of the design process and the defined design solution is considered the best regardless the manufacturing process and the production rate.

As an educational example, a re-design process has been carried out and finalized in order to compare, accurately, design alternatives after the conceptual design and so in the detail design phase. For this reason, complete 3D CAD models of the two examples have been built up for a comprehensive and detailed analysis.

4.1. Carousel Support

The carousel *Support* has been traditionally made by several steel plates welded together in order to create the desired geometry (metal working process). This assembly solution guarantees a good productivity without significant investment costs considering the low production rate of this part. *Aluminium monolithic block* is another possible solution for the carousel *Support* realization considering the approx. overall dimensions 2.5 x 1 x 0.5 [m]. This can be considered the best solution in terms of assemblability, but expensive in terms of material, equipment and manufacturing process. A CAD model of the two solutions have been built up (Fig. 4) for the analysis.

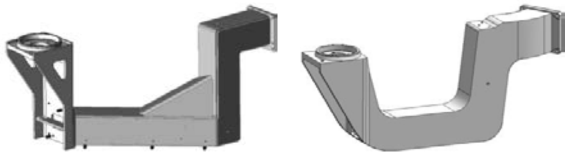

Fig. 4. CAD models of the *Support* (welded structure vs. monolithic block).

Table 1 summarizes the main components of the two different *Support* configurations.

Table 1. Components, materials and manufacturing processes for *Support*.

Component name	Material / Process / Investment	Welded		Monolithic	
		[pcs]	[€]	[pcs]	[€]
Welded structure	Carbon Steel / Welding	10	231,15		
	Weld. jigs (investment)		5,00		
Monolithic block	Aluminium / HPDC			1	121,06
	Die (investment)				200,00
Wire clamp	PP / Injection moulding	4	5,08		
Autosnap wire clamp	PP / Injection moulding	4	0,60	4	0,60
TOT.		*18*	*241,83*	*5*	*321,66*

4.2. Carousel Grippers

The carousel *Grippers* do not require particular structural properties but the possibility to be replaced due to possible damages or wear during their use. Each carousel have at least 16 *Grippers* and this means that the production rate of the *Grippers* is 16 times the production rate of the carousel itself.

Die casting process and Zinc alloy guarantee an excellent productivity and the use a rigid plastic material as a body cover (e.g. Acrylonitrile Butadiene Styrene - ABS) assures the wear resistance property. This is an excellent solution in terms of assemblability and manufacturability (material, equipment and process). A 3D CAD model of the two solutions have been built up and analysed in detail for the approach validation (Fig. 5). Few design changes have been done to reduce the part complexity and the number of components.

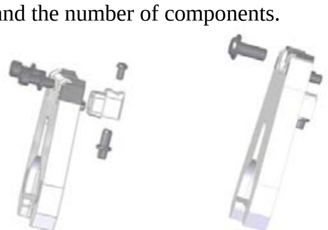

Fig. 5. CAD models of the *Gripper* (Casting piece Zn vs. Plastic piece).

Table 2 summarizes the main components of the two *Gripper* configurations. A total number of components and related costs are reported to compare the two alternatives.

Table 2. Components, materials and manufacturing processes for *Grippers*.

Component name	Material / Process	Casting Zn		Plastic	
		[pcs]	[€]	[pcs]	[€]
Body	ZAMAK alloy / Casting	1	0,96	1	0,96
Body cover	ABS / Injection moulding	1	2,93	1	2,93
Pin support	ABS / Injection moulding	1	0,36		
Pins	INOX / Turning, Grinding	1	0,54		
Screw TBEI M4x8	Galvanized steel / Turning	1	0,03		
Screw TCEI M6x18	Galvanized steel / Turning	2	0,06	1	0,03
knurling washer	Galvanized steel / Turning	2	0,002		
TOT.		*9*	4,88	*3*	3,92
TOT. (x 16 pieces)		*144*	*78,11*	*48*	*62,72*

5. Results discussion

The case studies previously presented are good examples to demonstrate the advantages of a multi-objective approach for decision-making during the early product design phase. The combined analysis of product manufacturing, assembling and cost during the early design phase allows the product development teams to deliver each time the best solution.

For the *Carousel Support*, even if the unitary manufacturing cost for the monolithic solution is cheaper, as well as the assembling phase is easier (less components), the initial capital investment is too bigger for the estimated production rate. The conclusion led the company to keep the original solution, while investigating further manufacturing processes with a lower initial investment.

For the *Carousel Grippers*, the new solution consisting in a new shape for the body cover is able to meet, at the same time, assembling, manufacturing and cost requirements, improving the old solution.

6. Conclusions

The proposed work aim to develop a multi-objective design approach for a comprehensive analysis of the manufacturing aspects (assembly, materials, processes, costs and times) in the conceptual design phase of complex products development. The approach is cost-driven and help designers and engineers in the selection of the cost-effective design solution.

A tool-holder carousel of a CNC machine has been analysed. The case study highlights how different design solutions can affect assemblability and manufacturability in terms of production time, manual operations and costs. As example, considering the *Carousel support*, even the *Aluminium monolithic block* is the best solution in terms of assembly time and cost, this is more expensive than the *Welded structure* which is considered the cost-effective solutions combining productivity, assemblability rate, manufacturing investments and complexity. This estimation has been carried out in the conceptual design phase by the use of rough product parameters (e.g. production rate). Furthermore, a validation process (re-design), with dedicated design tools, has been carried out to verify the outcomes of the proposed approach.

Future perspectives in this research topic will be a deeply validation of the method for other case studies and product typologies as well as the definition of a framework for the implementation of the proposed approach in a design tool based on mathematical model. A step forward will be to include other interesting production aspects such as environmental impacts, energy consumptions, etc. in order to shift the overall production features early in the conceptual design phase.

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