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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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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