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A multi-objective design approach to include material, manufacturing and assembly costs in the early design phase.

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Abstract

Conceptual design is a crucial activity in the product development process. The design freedom must consider a trade-off analysis among several aspects such as assembly, manufacturing, and costs. The goal of this approach is to define a multi-objective design approach for the determination of feasible design options. The approach is grounded on the concept of functional basis for the analysis of product modules and the theory of Multi Criteria Decision Making (MCDM) approach for the assessment of the best design option. A complex product (tool-holder carousel of a machine tool) is used as a case study to validate the approach.

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Keywords: Conceptual design, multi-objective design, complex products, design for assembly.

1. Introduction

Different Design-for-X (DfX) 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] [2]. However, these methods are rather laborious and in most cases, they require a detailed product design or an existing product/prototype. Other approach investigates the product assemblability starting from the product functional structure [3] [4]. In this way, the DfA technique can be applied during the conceptual design phase when decisions greatly affect production costs. 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 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, for example, from the assembly point of view but not cost-efficient in terms of manufacturing costs and investments. The novelty of this approach is to make systematic a random process which is currently based on the company know-how and experiences. Moreover, the mathematical model makes the approach repeatable and applicable in any manufacturing context.

§2 reports a brief review of the research background. §3 reports in detail the steps of the approach. A case study (tool-holder carousel) is analysed in §4. Results discussion and concluding remarks are reported in §5.

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2. Research background on target design methodology and multi-objective design

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 analyzed, then, the requirements are translated into product features, and finally, concepts that can satisfy the requirements are generated and modelled [5]. 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 product design [6] [7]. Manufacturing and assembly costs are decided during the design stage and their definition tend to affect the selection of materials, machines and human resources that are being used in the production process [8].

DfA is an approach which gives the designer a thought process and guidance so that the product may be developed in a way which favors the assembly process [9]. In the industrial practice, the Boothroyd and Dewhurst (B&D) is one of the most diffused DfA approach [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 [10]. Usually, DfA methods are applied in the detailed design phase when much of the design process has been deployed and solutions have been identified [11]. This is the main drawback of this approach.

Stone et al. [3] 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 [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 approach has two weak points: (i) the identification of best manufacturing process for part production and (ii) 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 Das et al. [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. DfA and DfM hardly integrate together, and the Design-for-Manufacturing-and-Assembly (DfMA) procedure can typically be broken down into two 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 [16].

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 [17]. However, the most accurate cost estimates are made using an iterative approach during the detail design phase [18]. While DtC is usually applied at the embodiment design or even worse in the detail design phase, to be efficient DtC requires to be applied at the same time of DfMA (conceptual design phase) [19] [20]. In this way, DtC is only an optimization of an already selected design solution from the manufacturing/cost point of view.

The only way to overcome the aforementioned issues is the multi-objective approach which takes into account all the production aspects (assemblability, manufacturability, materials, costs, etc.) at the same time. Different mathematical models can be used as a solver for the multi-objective problem. Multi Criteria Decision Making (MCDM) approach is one of the common approach for multi-objective problems [21]. Novelty of the proposed approached is based on the application of MCDM in the conceptual design phase to account multiple production aspects in the development of complex products.

3. The multi-objective conceptual design approach

The first step of the proposed approach is a standard practice in the conceptual design phase, that is the set out the product modules and properties considering the functional basis and the module heuristics. Then, by the concept of morphological matrix, a list of possible and feasible design solutions can be pointed out in order to fulfill the rows of the morphological matrix for each specific module. This step can be assisted and carried out using the company knowledge and the skills of designers and engineers. Finally, considering the multi-objective approach (DfA, DfM and DtC) based on the MCDM (Multi Criteria Decision Making) theory, 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 standard practice of DfA. It is important to highlight that the proposed approach is able to consider different target design methodologies (DfX) early in the conceptual design of product development process and not in the embodiment design or even worse in the detail design phase. In particular, the focus of this research work is related to the production (assembly, manufacturing, material selection and cost) aspects.

The steps of the proposed approach are detailed here below.

3.1. Step 1: Product modules definition and related properties

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. This is the first step of the conceptual design and helps designers and engineers in the definition of the product functions as well as in the identification of the overall product structure. The module heuristic identifies the in/out flows of each function.