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A multi-objective programming approach, integrated into the TOPSIS method, in order to optimize product design; in three-dimensional concurrent engineering

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A B S T R A C T

This paper proposes a new method to address a three-dimensional concurrent engineering (3D-CE) approach. It uses a Multi-Objective Linear Programming (MOLP) model integrated to the TOPSIS method in order to determine the best configuration product design, assembly process and suppliers of components. This method is able to involve various supply chain strategies by considering qualitative and quantitative criteria in the early stages of the new product development (NPD) process. It also applies the Fuzzy Analytic Hierarchy Process (FAHP) method to determine the relative importance of criteria defined to evaluate configurations of design alternatives, assembly processes and suppliers of components. A sensitivity analysis from different parameters in the model that affect the selection of the best design alternative is performed by creating a computer program using *visual studio*. A numerical example is used to demonstrate method efficacy and finally, the paper suggests some areas for future research.

1. Introduction

In recent years, the market environment has changed progressively due to increasing customer expectations and their demands for products with higher quality, lower price, better performance and shorter delivery time. To respond to these incremental pressures, companies are constantly looking for new strategies and methodologies to develop new products (Fine, Golany, & Naseraldin, 2005). The NPD process covers all activities from the development of an idea to the realization of the product during the production stage and its introduction into the market place (AIAG, 1995).

In traditional product development, the design of a product and production processes are done separately and sequentially (Portioli-Staudacher, Landeghem, Mappelli, & Redaelli, 2003). This serial pattern proposed solutions which had two important defects: it was slow as a result of not considering parallel process opportunities; it created a local optimum solution that was only suitable for sub-processes (Gunasekaran, 1998). Concurrent engineering (CE) is an efficient approach in the NPD process to decrease problems which can occur under sequential processes. In this approach, all the activities in NPD are integrated and carried out in parallel processes and by tools of CE, this process is continuously improving. CE has many advantages such as 30–60% decrease in time-to-market, 15–50% decrease in life cycle costs and 55–95% decrease in engineering change requests (Bopana & Chon-Huat, 1997).

Fine (1998) introduced the term "Three-Dimensional Concurrent Engineering (3D-CE)". This approach considers supply chain design together with traditional concurrent engineering. 3D-CE tries to consider, simultaneously, different aspects of design, process and supply chain in the early stages of product development. A supply chain is an integrated structure in which actions are performed to transform raw materials and components into final products and deliver them to customers. This chain is composed of suppliers, manufacturers, distributors, retailers and final customers (Chopra & Meindl, 2004).

Designers usually rely on their experiments to design a new product. They design a product with different components by considering technical, functional and operational criteria (e.g. size, ergonomics, cost, etc.) and usually without taking into account supply chain preferences. For example, a component provided from one supplier may have different specifications when compared to the same component from another supplier. These differences may impose restrictions that can affect design quality. A global optimal solution cannot be determined without considering supply chain preferences. In the early design stages, designers require a system to help them select materials or components, manufacturing/assembly processes and preferences of supply chain simultaneously.

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Decision making for activities of NPD process could be hard because it must be done during the preliminary design stages which are characterized by qualitative descriptions of requirements and imprecise data. There are also many qualitative and quantitative criteria that may affect the selection of a design alternative. In addition, there are many conflicting criteria to evaluate components/materials, processes and supply chain preferences. For example, the marketing department is interested in developing higher quality products to increase customer satisfaction. This could create a conflict with the manufacturing department that is interested in lowering manufacturing costs. There also could be conflict with the procurement department that may prefer to select low cost suppliers for components, which may result in lower quality levels. As a result, an appropriate concurrent engineering model should trade-off among different criteria (e.g. financial, engineering and supply) and at strategical, tactical and operational levels.

The rest of the paper is organized as follows: Section 2 discusses the past research work available in the area of the 3D-CE. Section 3 presents the background of the methods and techniques used in this work. Section 4 illustrates the proposed method. The efficacy of the proposed model is demonstrated by a numerical example in Section 5. Section 6 evaluates the sensitivity of the suggested model to changes using various parameters of the model. Section 7 represents the overall approach of the proposed model and suggests future research work.

2. Literature review

In recent years, some papers have studied the impact of product design, process and supply chain design on NPD process. Ellram, Tate, and Carter (2007) surveyed literature related to mutual fields of 3D-CE (product/process, product/supply chain, and process/supply chain) and wrote a good review of the 3D-CE.

CE approach has been an interesting topic for several years (Balasubramanian, 2001; Dowlatshahi, 1992; Gunasekaran, 1998). However, quantitative models in CE have not been studied very much. Lamghabbar, Yacout, and Ouali (2004) proposed a mathematical programming based on quality loss function to find the optimal values of the product and the process design. Schniederjans (1995) developed a goal programming approach in the CE environment by taking the objectives of cost and time into account. Xu, Li, Li, and Tang (2007) first evaluated attributes with Grey theory and proposed a fuzzy multi-stage decision making a system for product design in the concurrent engineering.

The CE models, usually, focus on product and process design, simultaneously. Researchers later recognized the need to incorporate supply chain design issues into product and process design. It led to the development of a new approach by Fine (1998) called 3D-CE. Huang, Zhang, and Liang (2005) integrated platform product decisions, manufacturing process decisions, and supply sourcing decisions. They developed a qualitative model by using a mathematical model to quantify the relationships among various design decisions and proposed a Genetic Algorithm (GA) method for solving their model. Petersen, Handfield, and Ragatz (2005) explained how to integrate suppliers into the new product development process and showed their impact on process design and supply chain decisions. Feng, Wang, and Wang (2001) developed a stochastic programming model to determine the tolerances of product design and selection of suppliers, simultaneously, based on quality loss. Fine et al. (2005), for the first time, proposed a goal-programming model to address 3D-CE and studied relationships between product structure (modular and integral) and supply chain structures (modular and integral). Wang, Huang, and Dismukes (2004) described the relation between specifications of a product and type of supply chain strategy and developed an integrated Analytic Hierarchy Process (AHP) and Pre-emptive Goal Programming (PGP) methodology for considering both qualitative and quantitative factors in the supplier selection. Fixon (2005) developed a multi-dimensional framework as a coordination mechanism that builds on existing product characteristics such as component commonality, product platforms, and product modularity. Nepal, Monplaisir, and Singh (2005) proposed a method based on fuzzy logic to model both product structure and supply chains based on information from the experts. Blackhurst, Wu, and O'Grady (2005) used a short network approach to develop the Product Chain Decision Model (PCDM) by considering decisions concerning product design and the manufacturing process and the impact of such decisions on the supply chain. Thomas, McKay, and Pennington (2006) reported information requirements that need to be met by using tools and techniques to support the execution of 3D-CE processes. Ellram and Stanley (2008) used the 3D-CE to integrate environmentally responsible manufacturing (ERM) and NPD and investigated positive effects of this integration. Ragatz, Handfield, and Petersen (2002) investigated the effect of the supplier integration process on cost, quality and new product development time. They showed that integrating suppliers into the NPD process has direct implications for process design decisions and for supply chain configuration decisions. They developed a conceptual model to integrate suppliers under technological uncertain conditions. Tchidi and He (2010) introduced an extended quality functional deployment process, in a 3D-CE environment that transforms customer requirements into product design, process design and supply chain design, through an extended house of quality.

Supply chain design as the third section of the 3D-CE includes different topics such as the selection of suppliers, distributors, plant locations, etc. This paper focuses only on the suppliers' selection. The supplier selection process is considered as an essentially multi-criteria decision making (MCDM) problem by taking into account taking different factors (Chamodrakas, Batis, & Martakos, 2010; Panta, Smirlis, & Sfakianakis, 2011; Razmi, Rafiei, & Hashemi, 2009; Vinodh, Anesh Ramiya, & Gautham, 2011).

In CE, so far, most works have been done on qualitative concepts and few papers have focused on applying multi-objective quantitative models. Furthermore, not many papers have integrated a supply chain design in the NPD process (Appelqvist, Lehtonen, & Kokkonen, 2004). Furthermore, none of these papers considers both qualitative and quantitative criteria for evaluating design alternatives in NPD. Thus, the aim of this paper is to fill this gap by developing a hybrid quantitative and qualitative model by using multi-objective linear programming (MOLP), TOPSIS and FAHP method. In this paper, we evaluate quantitative criteria by developing a MOLP problem and qualitative criteria (e.g. aesthetic, ergonomics, etc.) by using linguistic terms. Although, in the 3D-CE environment, we are able to consider many aspects of assembly/manufacturing and supply chains, in this paper, we focus on the assembly process and supplier selection. This paper, therefore, determines the best configuration of design alternatives, assembly processes and component suppliers.

3. Background

This paper uses several MCDM methods, including the fuzzy analytic hierarchy process (FAHP), the technique for order preference by similarity to an ideal solution (TOPSIS), and multi-objective linear programming (MOLP). These methods are described as follows:

3.1. FAHP

The FAHP (Van Laarhoven & Pedrcyz, 1983) is identified as an advanced version of AHP (Saaty, 1980) which considers fuzziness