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Technical paper

Comparative study of the applicability of fuzzy multi-objective linear programming models through cost-effective analysis for mold manufacturing

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ABSTRACT

The mold-manufacturing process consists of prototype design, production, assembly, and testing. As products tend to vary, have short due dates, and life cycles, are highly precise and must be responsiveness to customers, production system planning is complex and the relationship between outsourcing capability and in-house capacity is crucial to mold-manufacturing. Differentiation of core operations vs. non-core operations in internal vs. external environments and time control are essential for mold manufacturing when planning production systems. To analyze the cost-effectiveness of capacity planning and its relationship to suppliers, this work applies a novel fuzzy multi-objective linear programming model. Considered factors are order quantity allocation, due dates, manufacturing quantity, capacity, defect rates, back-log, and the purchasing discount. The applicability of three fuzzy theories is assessed using total costs, punishment costs, and crashing costs. Implementation results demonstrate the potentials for cost-effective capacity planning and outsourcing, and identify the applicability of these fuzzy theories to a specific mold-manufacturing case.

1. Introduction

Since the early 1960s, Taiwan's mold products have performed well as industrial exports. Almost all industries require support from the mold industry. However, since high-tech industries require highly precise molds, limited production, diverse models, short product life-cycles, and the need for rapid responses to customers have made decisions for mold production planning more complex than ever before. Low-end products are no longer competitive and high-end products are diversely impacted by changing production systems. Mold-production systems require technological evaluation in the design phase to enhance production efficiency and rapidly respond to customer requirements in the manufacturing phase. In the design or manufacturing phase, mold-manufacturing firms must examine product prototypes, evaluate part designs, and monitor manufacturing progress (Li et al. [1]). Further, order releasers are willing to be involved in the design phase to ensure adequate monitoring of outsourced manufacturing and acquire high-value products in competitive business environments (Cordero et al. [2]). Collaboration between mold firms and outsourcers is therefore important for the mold-manufacturing chain (Ybarra and Turk [3]). As many high-tech enterprises have global supply chains, Taiwanese mold firms must determine how to best develop a new strategy to maintain cost-effective manufacturing and upgrade products simultaneously. To develop a cost-effective production system, firms must adjust their make/buy ratio in outsourcing decisions and enhance manufacturing flexibility. As customers continually request improvements in product quality, factors in cost-effective decisions are extended to technological evaluations of outsourced firms. To retain customers and respond rapidly to their needs, mold firms must improve their productivity (Ni et al. [4]). Specifically, the make/buy ratios associated with quality improvement, due-date responsiveness, cost control, and supply flexibility must be considered. Thus, a cost-effective model is needed to analyze factor interactions. Conversely, a lack of technological expertise may cause production management problems related to lateness costs, rework costs, crashing, inspection, and product lifecycle (Lan [5]; Wang et al. [6]).

The mold-manufacturing process has three basic steps: initial product design; coarse electrical discharge machining (EDM); and, product forming. To establish competitive advantage, collaborative operations of vertical or horizontal alliances in outsourcing are crucial (Alemany et al. [7]). However, significant improvements in process efficiency may be achieved by process parameter optimization that identifies and determines regions of critical process-control factors, leading to desired responses with acceptable variations and ensuring reduced manufacturing costs (Montgomery [8]).

Outsourcing strategies are often utilized to satisfy demand within a limited capacity; however, firms should consider the

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technological variation environment. Capacity expansion and partial outsourcing are two strategies commonly used to meet market demands (Wang et al. [9]). Mold-production processes involve many planning steps with decision-making in different phases. Mold-manufacturing technology directly affects product quality, and manufacturers must continually optimize their development strategy based on cost-effectiveness (Law [10]). Additionally, mold manufacturing uses the make-to-order (MTO) production mode. As each product is unique, each technology must be examined, such that customer requirements can be satisfied (Raturi et al. [11]). A strategic alliance is critical to achieving competitive advantage (Ybarra and Turk [3]). To respond quickly to customer requirements, outsourced firms should be involved in designing products and share their knowledge and expertise (Andersen and Drejer [12]). Given a specific quality requirement, purchasing discount, and lead time with cost determinants, mold-production planners must evaluate production options under contractual requirements, manufacturing capability, and the capabilities of outsourced firms. To evaluate the effects of outsourcing and capacity-expansion decisions on cost-effectiveness while considering multiple parts and suppliers, this work applies a novel fuzzy multi-objective model. To evaluate uncertain factors related to mold-manufacturing characteristics, the fuzzy theories developed by Zimmermann [13], Hannan [14], and Yang et al. [15] are also implemented. The specific objectives of this work are as follows:

1. analyze the factors crucial to mold-outsourcing strategy;
2. develop a cost-effective model for evaluating manufacturing capability and outsourcing capabilities;
3. generate a fuzzy multi-objective model that incorporates contracted objects; and
4. assess the applicability of different fuzzy theories.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 formulates the mold-production and outsourcing-decisions problem as a linear programming (LP) model with fuzzy multi-objectives. Section 4 tests and compares the applicability of the proposed methodology with different fuzzy theories using a case study of a mold-manufacturing firm. Section 5 gives conclusions and recommendations for further research.

2. Literature review

Studies of mold-manufacturing processes are both numerous and diverse. This section reviews literature on mold manufacturing, production processes, and outsourcing cost-effectiveness as well as the relevant mathematical methods and applications.

2.1. Mold-manufacturing characteristics and manufacturing criteria

Technical selection of mold-manufacturing should consider the technological performance required for a mold to produce final parts in expected quantities with the intended quality. Economic issues and environmental impacts throughout a mold's life-cycle must also be considered (Pecas et al. [16]). Using computers to aid in the design and manufacturing processes is one solution that mitigates these limitations. However, the trend of small orders or small batch jobs may render expansive computer-aided equipment inefficient; however, collaborative operation can solve this problem (Ding and Matthews [17]). The effects of computer-aided equipment on lead-time reduction and process planning are significant, such that a lack of communication among activities may result in long mold-development times and incompatibility problems (Lee et al. [18]). Choy et al. [19] determined that each product's specification is unique, such that production processes vary from one product to another, increasing production schedule complexity. A mold manufacturer, therefore, must develop a cost-effective strategy for manufacturing flexibility with appropriate production time control.

Mold design directly affects part-production efficiency, and flow parameters such as temperature, pressure, velocity, and time are important to mold quality (Macdonald and Wang [20]). Controlling lead-time is beneficial to various product phases. During the manufacturing phase, a manufacturer must rapidly respond to customer requests and conduct a cost analysis that considers outsourcing decisions, technological evaluation, and due-date control. Furthermore, designing mold-production systems is difficult due to small batch production and the product diversity in each lot. Particularly, the strength of an outsourced supply chain typically dominates the success of order production (Choy et al. [19]).

Mold outsourcing decisions are highly relevant to cooperation between fabrication capability and outsourcer capability with technological and experience factors requiring a multi-criteria evaluation process. Identifying outsourcing firms is crucial to supply chain design. Factors considered in decision processes include make/buy decisions, vendor selection, contractual negotiation, collaborative design, purchasing analysis, and source analysis for mold manufacturing (Aissaoui et al. [21]). Choy et al. [19] demonstrated that during production processes, mold firms must manufacture specific products using specific production systems within desired deadlines. Production planning thus becomes an important process for avoiding delays and ensuring that a schedule is met. Although, the problem of outsourcing decisions is a multi-criteria problem, multi-criteria techniques are rarely applied to solve this problem (Wadhwa and Ravindran [22]). Selection of outsourcers requires an evaluation of production-capacity planning for both makers and vendors, and time control is crucial to cost-effectiveness.

Mold-manufacturing firms must deliver products to customers within a limited period (Ni et al. [4]). Thus, mold manufacturers should develop strategic alliances to strengthen their competitive advantage (Lin [23]). As the pressure associated with short production lead-time increases and technological requirements change, mold firms may not determine their production decisions within limited periods. Therefore, cost variation in a production schedule is strongly related to the control of lead-time and crashing factors. Specifically, evaluating supplier technological capability, generating an efficient schedule, and making production and planning decisions, are critical because cost-effectiveness is based on their interactions. As decisions can be biased or incorrect, an evaluating model is needed that can analyze uncertain factors.

2.2. Application of fuzzy set theories

Fuzzy set theory was initially developed by Zadeh [24] and later refined and applied by Bellman and Zadeh [25] to solve decision problems with uncertain characteristics. Since then, various theories have been developed, and fuzzy multi-objective programming (FMOP) methods have been applied to factor- or parameter-related problems in formulated models with uncertainties that cannot be precisely estimated in reality. Zimmerman [13] summarized the implementation steps in multi-objective programming and applied a linear membership function to represent and integrate each fuzzy objective. The formulated problem was then converted into a LP computable presence. The applicability of FMOP has been expanded by many studies and then applied to solve imprecise problems in many fields. For instance, Slowinski [26], Teng and Tzeng [27], and Chiampi [28] applied FMOP to the design of a water pipeline systems and transportation projects, respectively. Huang et al. [29] developed a multi-objective programming model for partner