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A Stackelberg game in multi-period planning of make-to-order production system across the supply chain

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ABSTRACT

Mass customization becomes an emerging trend in numerous industries. With this, firms are adopting the make-to-order production strategy to allow ease of producing product varieties. This study adopts a game theoretic approach in analyzing a supply chain which consists of a manufacturer with multiple suppliers. The manufacturer has an exclusive supplier for every required component of its final product. The manufacturer may also consider for a third-party subcontractor to produce a fraction of its demand. The game is dynamic in nature wherein the interactions and decisions of the firms are observed in multiple time periods. Relevant to the make-to-order environment, price and lead time market elasticity are considered. The vertical interaction within the supply chain, between the manufacturer and its suppliers, is played as a leader-follower game. On the other hand, multiple scenarios are investigated such as constant selling price, limited workforce, and safety stock considerations to further provide managerial insights between the interactions of the supply chain members. In order to test the applicability of the proposed model, we present a case study of a local advertisement supply chain in the central Philippines. Finally, the results are interpreted to provide key managerial insights and conclusions.

1. Introduction

With the growing interest in product varieties, more firms are looking at capitalizing on this trend by implementing make-to-order (hereafter MTO) production strategies which allow for greater product variety and flexibility. Product customization is the production of goods and services that meet customer requirements [11]. The development of product customization and individualization stems from the need for differentiation and that luxury is continually increasing. Product customization leads to providing customers with a variety of products to choose from and thus, giving a sense of uniqueness. Although similar raw materials are required in producing the final outputs, customizing the production process may also result in providing product varieties. Furthermore, the more people that possess the same product, the less valuable or attractive the product would become [4]. Pine [33] compared mass production and customization, and stressed that mass production is considered a safer option; however, it would lead to higher costs and longer cycle times. On the other hand, moving for customization results in greater variety at lower costs. Greater product variety and flexibility would also lead to higher customer satisfaction [11]. Due to the increasing trend of customization in the consumer market, numerous firms are implementing MTO production strategies.

When optimal decisions on MTO production strategies are determined in the context of the supply chain, current literature adopts game-theoretic approaches, e.g. Qin [35], Leng and Parlar [24], Xiao et al. [46,48], and Xiao et al. [47]. In the recent years, game theory has been used to study interactions among rational firms in a supply chain and even between supply chains and Stackelberg games are widely used [17]. Game theory is a branch of applied mathematics that formally studies decision-making situations where two or more decision makers are involved [40]. In fact, game theory is the preferred choice of studying supply chain optimization because any supply chain structure consists of at least two firms. Moreover, it is necessary to use game theory instead of other basic decision-making techniques(e.g. single-objective optimization) since these techniques fail to consider the interaction between firms and are only able to consider a single decision maker, making them inadequate for studying supply chains in real-life

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Nomenclature

Sets/Indexes

n	Components of manufacturer n ∈ {1,2. . .,N}
t	Time periods t ∈ {1,2. . .,T}

Objective Functions

π_m	Profit function of manufacturer
π_n	Profit function of supplier *n*
π_{sc}	Profit function of entire supply chain

Decision Variables: Manufacturer's primary decisions

Q_m^t	Production quantity in period *t*
Q_s^t	Subcontract quantity in period *t*
q_n^t	Order quantity for component *n* in period *t*
p^t	Selling price in period *t*
Wf_m^t	Workforce level of manufacturer in period *t*

Decision Variables: Supplier's primary decisions

$\tilde{q}_n^t$	Order quantity of supplier *n* in period *t*
Wf_n^t	Workforce level of supplier *n* in period *t*

State Variables

C_m^t	Unit cost of manufacturer in period *t*
τ^t	Lateness in lead time in period *t*
L^t	Lead time
T_m^t	Manufacturer's production time in period *t*
u_n^t	Manufacturer's inventory level of component *n* in period *t*
$\tilde{u}_n^t$	Inventory level of supplier *n* in period *t*
T_n^t	Production time of supplier *n* in period *t*
C_n^t	Purchasing cost of supplier *n* in period *t*
Sm_n^t	Setup cost of manufacturer in period *t* for n^{th} component
S_n^t	Setup cost of supplier *n* in period *t*

Parameters

α	Maximum demand for final product
β_1	Price elasticity of demand
β_2	Lead time elasticity of demand
w_n^t	Wholesale price of supplier *n* in period *t*
p_s	Unit subcontract cost of manufacturer
λ	Unit penalty cost per duration of lateness
L_u^t	Maximum lead time quoted by market in period t
Hm_n	Unit holding cost of manufacturer for n^{th} component
Sm_n	Setup cost of manufacturer for n^{th} component
H_n	Unit holding cost of supplier n
S_n	Setup cost of supplier n
C_p^t	Total production cost of manufacturer in period t
D^t	Market demand in period t
k_n	Number of component n to produce one unit of manufacturer's output
θ_m	Manufacturer's cost to add an additional worker
θ_n	Cost of supplier n to add an additional worker
φ_m	Speed of manufacturer's workforce (unit/hr/worker)
φ_n	Speed of supplier n's workforce (time/worker/unit)
ν_n	Number of a certain type of raw material in one unit of component n
$h\left(\tilde{q}_n^t\right)$	Supplier's decreasing function of price discount

scenarios. In MTO supply chain scenarios, a limited number of studies exist in domain literature. Majority of works aimed at optimizing pricing and ordering decisions; however, there is a limited number of studies that consider workforce and inventory levels which arguably impact production costs. Various works on game theory applications consider make-to-stock supply chains with a limited focus on the MTO strategy which is popular in large industries such as apparel, furniture, office equipment, and automobile [47]. While on-time deliveries are crucial in these industries and the occurrence of late deliveries is likewise relevant; unfortunately, a limited number of studies that focus on late delivery lead times and its penalties exist in the literature. Finally, most supply chain games are static in nature and they fail to consider multiple time periods which is relevant to production planning activities.

Thus, this paper attempts to develop a game theoretic approach to optimize the pricing, production and ordering decisions of supply chain firms using MTO systems. The main departure of this study from the current literature is to model an MTO supply chain with a single manufacturer and multiple suppliers using a Stackelberg game to optimize the strategic decisions of the players across multiple time periods. It further extends the literature in this area by introducing production decisions such as the production quantity, workforce and inventory levels of firms, in addition to pricing and ordering decisions. These features of the proposed model would be useful for realistic MTO supply chains in helping them optimize their practical supply chain decisions. The initial framework which this work is based upon is presented by Vasnani et al. [43]. In this work, we present an elaborate discussion as well as a real-life case study along with some scenario analyses in order to gain managerial insights of the proposed framework.

The remainder of this paper is organized as follows. The next section presents a brief review of the related literature. In Section 3, the proposed model and game description is provided. This section also contains the assumptions in formulating the general model. In Section 4, a case study is presented together with a detailed solution and computational results. Also in this section, sensitivity and situational analyses are constructed to provide meaningful managerial insights. Finally, the paper concludes in Section 5 with some suggestions for future work.

2. Background of the study

Supply chains are complex systems involving firms, activities, information and resources that aid the movement of a commodity through all the members in the supply chain (e.g., from a supplier down to a customer) [30]. The members of the supply chain make particular decisions, such as price and quantity decisions, that potentially impact the entire supply chain [10]. This means that a supply chain is largely reliant on its members to function effectively and efficiently. With this, supply chain scenarios always have two or more decision- makers and such decisions are subject to game theory [40]. Game theory has been used to analyze various supply chains. Qi et al. [34] looked into a supply chain with one manufacturer and two competing retailers using the Cournot and Stackelberg game models. On a larger scale, Mahmoodi and Eshghi [27] studied the price competition between two supply chains with one manufacturer and one retailer each, using a model similar to Bertrand's price competition model [3,27]. Recently, protecting the environment has become a major concern. With this, recent studies including Gao and You [13,14], Ma and Wang [26], Yue and You [52,53], and Gao and You [13,14] highlighted works on multi-echelon and closed-loop supply chains. These works emphasize on the adoption of triple-bottom-line focusing on social, environmental, and economic supply chain performance.