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Yiyo Kuo Taho Yang David Parker Chin-Hsuan Sung

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Integration of customer and supplier flexibility in a make-to-order industry

Yiyo Kuo
Department of Industrial Engineering and Management, Ming Chi University of Technology, New Taipei City, Taiwan
Taho Yang
Institute of Manufacturing Information and Systems, National Cheng Kung University, Tainan, Taiwan
David Parker
Business School, University of Queensland, Brisbane, Australia, and
Chin-Hsuan Sung
Institute of Manufacturing Information and Systems, National Cheng Kung University, Tainan, Taiwan

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Abstract

Purpose – The purpose of this paper is to solve an integration of customer and supplier flexibility problem in a make-to-order (MTO) industry. The flexible strategies, where delivery leadtime and unit price (or raw material cost) can be negotiated, are provided by customers and suppliers. Its effectiveness is illustrated by a practical application.
Design/methodology/approach – The present study is a rolling decision-making problem and is solved by a proposed combined mixed integer program (MIP) and simulation approach. A simulation model was developed for evaluating solutions of the MIP and will serve as the virtual factory to provide the initial work-in-process status for a new incoming order evaluation.
Findings – The experimental results show that when either customers or suppliers provide flexible strategies to the manufacturer, total profits can be increased. Moreover, when both customers and suppliers provide flexibility strategies to the manufacturer simultaneously, total profits can be significantly increased.
Research limitations/implications – An expanded experiment would be of help in realizing the relationship between the flexibility and profit. Moreover, there are other price-sensitivity functions for both customers and suppliers.
Practical implications – A fishing-net manufacturing company was used for the case study to illustrate the effectiveness and the feasibility of the proposed methodology and its application to industry.
Originality/value – The proposed methodology innovatively solved a practical application. The customer and supplier flexibility was investigated in a MTO production system that has no inventory of raw material. The experimental results are promising.

Keywords Simulation, Flexibility, Supply network, Supplier selection, Pricing, Mixed integer programming
Paper type Research paper

1. Introduction

Today, ever increasing numbers of companies are providing large varieties of products to meet diversified customer needs (Zhang and Tseng, 2009). Additionally, an increased demand for specialized products has led to a growth in the number of make-to-order (MTO) companies (Stevenson *et al.*, 2005; Charnsirisakskul *et al.*, 2006; Gharehgozli *et al.*, 2008).

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MTO implies that the production process starts when a purchase order is received and accepted. Since the flow of materials is only triggered by customer orders, MTO needs to be flexible since their operations are always subject to a variety of uncertainties: such as customer demand and supplier capacity (Chan and Chan, 2010). Therefore flexibility is one of the main competitive features of MTO firms. However, most literature related to flexibility in MTO focus on the flexibility inside the manufacturing system, especially capacity flexibility (Tanrisever *et al.*, 2012), with literature related to flexibility outside the MTO manufacturing system being rare.

In an MTO system the focus of production planning is on efficiencies in the execution of orders. Moreover, performance measures concentrate on progress of the order, e.g. average response time and average order delay within a supply chain management context (Xu *et al.*, 2009). The competitive priority is based upon a shorter delivery leadtime (Soman *et al.*, 2004). Consequently, a shorter leadtime may attract greater numbers of customers and generate more demand. However, it places pressure on the firm's production resources and invariably increases production unit cost. Customers, however, might be willing to wait longer if they are offered lower prices (Pekgün *et al.*, 2008; Teimoury *et al.*, 2011). When customers accept increased leadtimes and a lower price simultaneously, within prescribed ranges and without affecting customer satisfaction, this phenomenon can be categorized as customer flexibility (Zhang and Tseng, 2009). When a customer accepts a lengthier delay with slight price decrease, it suggests higher customer flexibility.

During the order commitment process, manufacturers have to estimate the leadtime of orders to establish delivery dates and prices. Long-term success of the MTO may depend upon its ability to accurately determine leadtimes given the firm's available capacity and backlog (Easton and Moodie, 1999). The delivery leadtime in a MTO system includes manufacturing, assembly and shipping (Arnold *et al.*, 2008). In general, the leadtime related to manufacture and assembly is dependent on inventory (e.g. finished goods stock, raw material and work-in-process (WIP)), capacity (e.g. number of machines, labor and shifts), and previously accepted orders. However, sometimes inventory of raw material causes additional holding costs; consequently, for manufacturing processes, their raw materials are only ordered from the supplier once they receive a customer's order. Therefore, the leadtime for ordering raw material must also be taken into consideration when estimating the delivery date for the customer. As regards the leadtime related to shipping, it is dependent on the distribution system and location of suppliers and customers; with speed of delivery being a measure of effectiveness. Therefore, issues regarding the manufacturing, assembly and shipping will all affect the estimating the leadtime of orders to establish delivery dates and prices. Logistical considerations that encompass physical distribution of goods and leadtimes for transportation are generic factors that create considerable challenges across numerous industries and commercial sectors (Xu *et al.*, 2009).

As with customer flexibility, the leadtime and unit price of raw materials ordered from suppliers can be altered within prescribed ranges. The consequence of reducing the leadtime for the raw materials is increased cost. If a supplier agrees to deliver the raw material at a reduced leadtime with only a slight increase in the unit price of raw material, it represents higher supplier flexibility.

This research integrates the concept of customer and supplier flexibility, and compares system performances of alternative strategies: where either customer flexibility or supplier flexibility dominates. The novelty and uniqueness of exploring these variations in manufacturing dynamics is confirmed in the literature dealing with customer and supplier flexibility. We are not aware of any existing research that examines the effect of simultaneously integrating customer flexibility and supplier flexibility.

The inherent stochastic features of manufacturing systems and their non-trivial dynamics and associated complexities – for example, plant capacity, set-ups, disruptions, etc. – are a reality of any commercial enterprise. Simulation typically is used when the stochastic system involved is too complex to be analyzed satisfactorily by a mathematical model (e.g. queueing model) (Hillier and Lieberman, 2010). Discrete-event simulation can model a non-linear and stochastic problem and allows examination of the likely behavior of a proposed manufacturing system under prescribed conditions (Yang *et al.*, 2011).

This research focusses on the manufacturer's rationale in decision making. A combined mixed integer program (MIP) and simulation approach is proposed for this problem. This is described as a rolling-planning problem. The WIP information is incorporated in the simulation model and will serve as the initial condition for a new incoming order. The MIP then provides evidence on which to accept or reject the order from a customer, which supplier to source the raw material from, the due-date of finished goods to the customer, the unit price of finished goods, the delivery date of raw material from the supplier and the unit cost of raw material. To allow testing, a practical application from fishing-net manufacturing was adopted for the empirical illustration.

Thus, the proposed methodology aims to be an effective decision support system for the proposed supply chain management problem. A MIP model is first developed that takes customers' and suppliers' flexibility into consideration simultaneously to maximize the profit in a MTO environment. Since the MIP model uses deterministic data, it tends to find a capacity-wide feasibility solution and to predict the potential profit. Then, the simulation model takes the practical stochastic data and constraints into consideration to find the expected profit, which is then validated by a practical application. Moreover, performance measures concentrate on progress of the order, e.g. average response time and average order delay within a supply chain management context (Xu *et al.*, 2009).

The remaining sections of this paper are organized as follows. In Section 2, the literature focussing on customer flexibility and supplier flexibility is reviewed. Next, in Section 3, an MIP that takes customer flexibility and supplier flexibility into consideration is proposed. The interface between the simulation model and the proposed MIP is also introduced in Section 3. Following on in Section 4, the case study of a fishing-net supply network is introduced. Experimental results are reported in Section 5; followed by summary and concluding remarks in Section 6.

2. Literature review

In most organizations profit is significantly affected by purchasing. The proportion of revenue spent on indirect purchases may be 20-30 percent (Kaplan, 1984; Adler, 1987; Kapoor and Gupta, 1997; Hilmola, 2005). It has become evident that companies can no longer afford the luxury of maintaining large quantities of inventory. This has led to the introduction of material requirements planning (MRP) systems for rationalizing and scheduling components and assemblies (Umble *et al.*, 2003; Zäpfel, 1996; Segerstedt, 1996; Mabert, 2007; Ioannou and Dimitriou, 2012). A variable in the MRP system is the method to determine how much to order, and time to order (Lee and Adam, 1986).

The subsequent generation, MRP II (manufacturing resource planning) is an enterprise-wide, closed-loop manufacturing control system which integrates all aspects of manufacturing – material control, shopfloor control, requirements planning, finance, marketing and personnel (Wilson *et al.*, 1994; Umble *et al.*, 2003). In contrast, enterprise resource planning (ERP) allows companies to integrate various departmental information (Gupta, 2000); that uses database technology to control and integrate all the information related to a company's business including customer, supplier, product, employee and financial data (Helo *et al.*, 2008). Notably, ERP is applicable for any company in need of integrating their information across functional areas (Abdinnour-Helm *et al.*, 2003). However, it does not provide full support for the integration and co-ordination of production planning and control activities in global supply networks (Xu *et al.*, 2009).

An important consideration in this study, particularly in the context or MRP/ERP, is available-to-promise (ATP) (Ioannou and Dimitriou, 2012). ATP is a business function that provides a response to customer order enquiries, based on resource availability (Ball *et al.*, 2004). It generates available quantities of the requested product, and delivery due-dates. Therefore, ATP supports order-promising and fulfillment, aiming to manage demand and match it to production plans. In the case used in this work, ATP execution may need to be adjusted for the way a company operates.

A fundamental distinction between ATP functions is based on the push-pull strategy. Push-based ATP is based on forecasts regarding future demand. Based on anticipation of demand, ATP quantities and availability dates are computed. An example is the traditional determination of ATP based on the Master Production Schedule (Zhao, 2005).

Pull-based models dynamically allocate resources in response to actual customer orders. This means that pull-based ATP is able to balance forecast-driven resource replenishment with order-triggered resource utilization (Zhao, 2005), but because resources are allocated with each coming order, the process will yield limited results.

ATP functions can be executed in real time, driven by each individual order, or in batch mode Mabert (2007), meaning that at a certain time interval, the system checks availability for orders piled up in that period of time. The process is triggered by the need to check resource availability before making a commitment to deliver an order.

In contrast, the basic function of available-to-promise (ATP) is different from MRP/MRP II/ERP. ATP activity is identifies the delivery date promise to customers for their specific order (Jeong *et al.*, 2002). When a new customer order arrives, ATP determines whether the schedule has enough available finished products (subassemblies), inventory; and any shortfall needing to be produced has components and raw materials available to deliver the order on time (Xiong *et al.*, 2003). Therefore, ATP is a business function that plays a prominent role of directly linking customer orders with enterprise resources and, therefore, must evaluate the trade-off between front-end and back-end performance (Ball *et al.*, 2004). It provides product availability information for order-promising and order-fulfillment decision support to increase the revenue (Chen *et al.*, 2002; Meyr, 2009). The development of ATP methods and their application to support order-promising has primarily been driven by providers of ERP and Advanced Planning Systems (Pibernik, 2005). However, the decision of order-promising and order-fulfillment are also influenced by a customer's tolerance to waiting. For instance, a customer may be willing to trade-off the increased leadtime and the decreased cost (Brabazon *et al.*, 2010; Brabazon *et al.*, 2012).

The aim of the present study is to analyze the impact of price and delivery flexibility of customers and suppliers to the total profit. Two streams of research are highly related to our work: customer flexibility, and supplier flexibility.

Customers are often indifferent to certain product specification and are willing to accept products with less desirable quality and functional attributes in exchange for a price discount. This extra degree of flexibility in meeting customers' product specifications, which is termed customer flexibility, provides a way for manufacturers to improve profit by making better utilization of manufacturing and supply resources (Cui, 2015). The customer flexibility can be characterized through two dimensions: range and response (Zhang and Tseng, 2009). That means that within the customer acceptable range it would have little impact on customer response (Wang and Tseng, 2014). Mak *et al.* (2011) point out that it is important for manufacturers to exploit the advantages of customer flexibility to the full in selecting their suppliers and locating orders to selected suppliers. Customer flexibility in this research relates to when customers influence the production of manufacturers by adjusting the unit price and due-date, and subsequently decide to accept or reject the order. Evidence of this phenomenon can be found in the pricing literature.

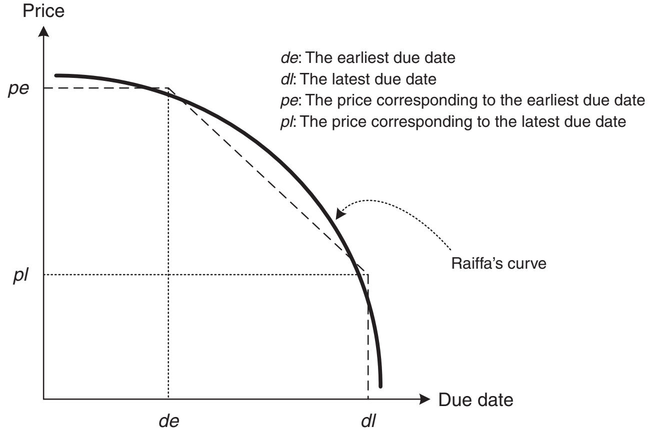
With regard to supplier flexibility in a supply chain, the suppliers' flexibility is considered as a tool to cope with the environmental uncertainties (Chan *et al.*, 2009) or the ability to manage disruptions and respond better to fluctuating demands (Rajesh and Ravi, 2015). Chu *et al.* (2012) suggest that supplier flexibility has a significant positive impact on the performance of manufacturers. As the results from Avittathur and Swamidass (2007) show, the profitability is above average when a flexible plant uses flexible small suppliers. In contrast, if there is a mismatch of plant flexibility with supplier flexibility, the profitability is below average. In this research, the unit cost of raw material can be adjusted according to the length of leadtime – allowing manufacturers to select the suppliers who provide the best offer. The manufacturing strategies of suppliers could be MTO or MTS. Due to the production process starting when a purchase order is received and accepted in MTO, the finished goods inventory is held in MTS. A MTO manufacturing system would have a longer leadtime but a lower holding cost; compared to a MTS manufacturing system that provides a shorter leadtime but a higher holding cost. As regards price, various factors are taken into consideration and not solely manufacturing strategies. Consequently, supplier selection would be dependent on the requirements of each order. This strategy is addressed in the supplier selection literature.

On a more general point regarding the relevance of this research, in the context of efficient SCM, social economic development and the implications of associated benefits, it has been argued that the non-trivial relationships between customers and multi-tiered suppliers has not been sufficiently analyzed (Xu *et al.*, 2009). Productivity improvements in supply chain relationships afford significant economic opportunities. The quantitative appraisal of this research indicates clear benefits that can be gained.

In the following section, literature is reviewed that focusses on pricing and supplier selection, with the purpose of explaining the related trade-off between price and leadtime.

2.1 Pricing related to trade-off between price and leadtime

Moodie and Bobrowski (1999) proposed a model for demand management in a job shop. They argued that the relationship between the due-date and price, represented as a maximum trade-off curve that is a critical market-based scenario. Figure 1 shows the



Source: Raiffa (1982)

Figure 1. Maximum net price to due-date trade-off curve

trade-off relationship. The plot in Figure 1 closely matches Raiffa's (1982) quarter circle curve for the trade-off between two factors in negotiations. The maximum accepted unit price for customers between earliest and latest due-date reduces as the due-date increases. For any date between earliest- and latest-due-date, and if the unit price is under the curve, the price will be accepted by customers.

The model of Ray and Jewkes (2004) represents an operating system consisting of an organization and its customers, when first, the mean demand rate is a function of the guaranteed delivery time and market price, and second, price is dependent on the length of the delivery time. The objective of the model is to maximize profit by selecting an optimal guaranteed delivery time. The results show that the time-based competitive strategy for firms whose customers are more sensitive toward price than delivery time will be different from those whose customers want a shorter delivery time and are ready to pay a price premium. Therefore, they suggest that manufacturers would need to understand customer characteristics – based on the simultaneous dependence of price and the demand on delivery time before they decide a delivery time strategy.

Watanapa and Techanitisawad (2005) proposed a bidding model to maximize the expected revenue for the MTO firm. Both due-date and price can be dynamically adjusted within a predetermined range. However, the setting of both price and due-date can influence the customer satisfaction. A low price and reduced due-date will increase the firm's competitive advantage, resulting in a higher probability of winning the order.

Charnsirisakskul *et al.* (2006) developed a decision model which considers leadtime, inventory, price, scheduling and order acceptance to maximize the total profit. The profit comprises total revenue minus production cost, inventory cost and a tardiness penalty. An order is divided into several sub-orders and can be delivered separately. Unit prices of all sub-orders are the same. An early or late completed sub-order will attract an inventory cost or tardiness penalty. The higher the unit price, the higher the inventory cost and tardiness penalty per unit.

Zhang and Tseng (2009) proposed a MIP to maximize the overall profit – incorporating the total revenue minus inventory and overtime cost, and where the unit price is dependent on the leadtime. Their assumption is similar to Moodie and Bobrowski (1999). The longer the leadtime, the lower the unit price is. The use of an overtime strategy can reduce the leadtime but will increase labor costs.

Özlük *et al.* (2010) proffers smoothing demand by offering price incentives to those flexible customers. A MIP is proposed to minimize total cost – which is the sum of fixed labor, overtime, temporary labor and price incentives cost. Such flexible customers would invariably like to be serviced early or late by paying less money. Thus, the range between low and peak demand can be reduced.

Kalantari *et al.* (2011) proposed a decision support system for order acceptance/rejection in a hybrid make-to-stock/MTO production environment. In the system, a set of guidelines are proposed to help the organization negotiate over price and due-date with the customers. One of the guideline suggests reducing the delivery time by adding extra costs to the price of the order; and another one suggests reducing the order price by increasing delivery time.

Xiao *et al.* (2014) developed a game theoretic model of a one-manufacturer and one-retailer supply chain facing an outside integrated chain (manufacturer) to study the price and leadtime competition and investigate co-ordination of the supply chain, where the MTO production mode is employed and consumers are sensitive to retail price and leadtime. They found that a higher reservation price or brand differentiation increases the retail price but decreases the leadtime; a higher transportation cost or lower leadtime sensitivity increases the retail price and the leadtime.

2.2 Supplier selection related to trade-off between price and leadtime

The supplier selection problem is defined as identifying which supplier should be selected and how much order quantity should be assigned to each supplier (Weber and Current, 1993). Traditionally, suppliers are selected based on their ability to meet the quality requirements, delivery schedule and the price offered (Sevkli *et al.*, 2007). It is often a multiple criteria decision-making problem (Yang and Hung, 2007; Yang and Lu, 2011; Li *et al.*, 2008). However, there is limited literature relating to supplier selection and supplier flexibility. For example, Lee (2009) proposed a fuzzy analytic hierarchy process to rank five backlight unit suppliers of a TFT-LCD manufacturer. Chou and Chang (2008) present a fuzzy simple multi-attribute rating technique (SMART) approach for solving the supplier selection problem. Lee *et al.* (2009) first applied Delphi to differentiate the criteria for evaluating traditional suppliers vs a green supplier. A fuzzy extended analytic hierarchy process was constructed next to evaluate green suppliers for an anonymous TFT-LCD manufacturer. This extant research, however, did not consider the supplier's flexibility as one of the criteria; nor was the trade-off between price and leadtime taken into consideration.

Literature related to supplier selection and the trade-off between price and leadtime is sparse. Hassini (2008) proposed a linear programming model for minimizing the total purchasing costs; with the supplier's capacity and price discount both being dependent on leadtime. In this example, the proposed linear programming restricts the unit price by allowing a later due-date, but does not allow an earlier due-date. This results in an increased leadtime causing a lower price. Therefore, for the buyer, the longer the leadtime, the lower the raw material cost.

Das and Abdel-Malek (2003) proposed a model for measuring the flexibility of suppliers. The measurement of the flexibility is affected by a minimum delivery leadtime, Lm, minimal order quantity, Qm, expedited delivery penalty, α, and order quantity reduction penalty, β. If orders needed to be delivered faster than the minimum delivery leadtime or orders are below the minimum quantity, then a price penalty is imposed. For example if $\alpha = 4$ percent per day, then that would imply a 12 percent unit price penalty if delivery was scheduled three days earlier than L_{min}. Moreover, if

$\beta = \$10{,}000$, and an order for 80 percent of Q_{min} was received then there would be a penalty of 2,000 (10,000 × (1-80 percent)). Liao and Rittscher (2007a) then combined the measurement index of supplier flexibility proposed by Das and Abdel-Malek (2003) with an index representing total quality, total delivery and total cost to propose a multi-objective model for solving a supplier selection problem.

There is an extensive literature addressing flexibility of supply chain networks, but no account was found that discusses, simultaneously, how to solve pricing to customers (customer flexibility) and supplier selection (supplier flexibility).

3. Proposed methodology

For the modeling purpose, we define the required notation below. The overview of the proposed combined MIP and simulation approach is illustrated in Figure 2 followed by a detailed step-by-step discussion of the proposed methodology.

Notation:

de = minimum accepted due-date
dl = maximum accepted due-date
pe = unit price for minimum accepted due-date
pl = unit price for maximum accepted due-date
d = due-date
p = unit price
Lm_j = minimum delivery leadtime of supplier j
α_j = expedited delivery penalty of supplier j

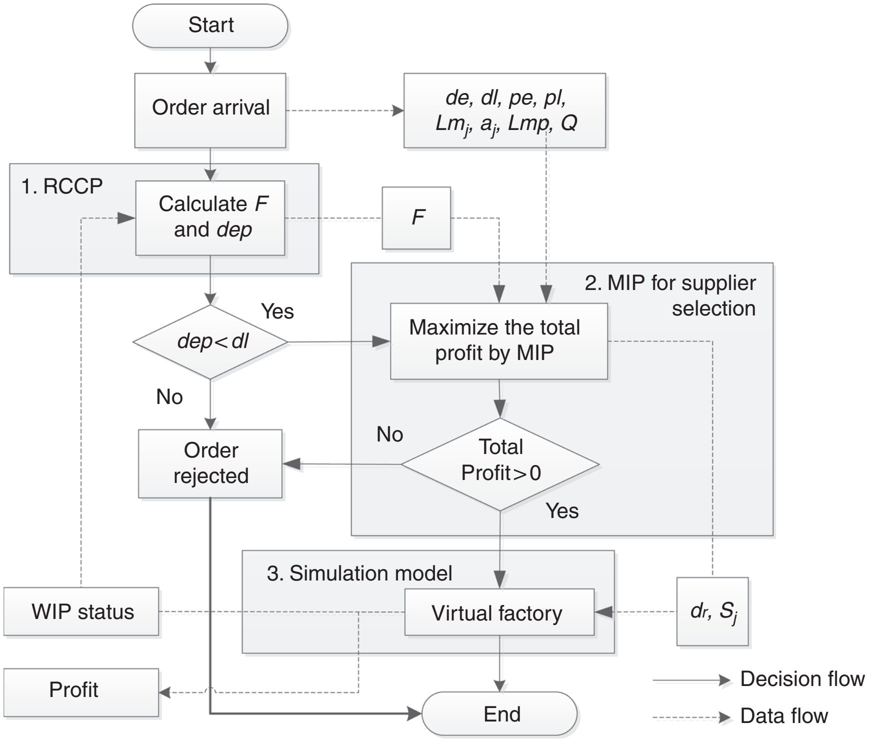


Figure 2.
The relationship between simulation model and MIP

dr = leadtime of the raw material
t_j = lateness of supplier j
m_j = raw material cost of supplier j
Q = quantity of the order
c = production cost per unit
F = total production time of the order
Lmp = possible minimum leadtime of all suppliers
$$S_j = \begin{cases} 1, & \text{if supplier } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$
$$A_{ki} = \begin{cases} 1, & \text{raw material type of order } k \text{ is } i \\ 0, & \text{otherwise} \end{cases}$$
Q_k = quantity of order k
PT_{iw} = processing time per unit of raw material i in workstation w
dep = possible earliest due-date

The proposed methodology is for a rolling-planning decision. We begin with the building of a simulation model to serve as the virtual factory for the case company. Since it is a rolling-planning problem, the existing WIP status in the factory (simulation model) is the initial condition for a new incoming order. The simulation model mirrors the practical manufacturing process and consists of the required detailed data. Thus, it can serve as the virtual factory of the case problem for the analyses.

There are three decision modules: rough-cut capacity planning (RCCP), MIP for supplier selection and simulation model. The RCCP module uses the data of WIP status in the simulation model to estimate whether the existing capacity can satisfy a customer's due-date requirement (Hopp and Spearman, 2008). If the capacity can satisfy a customer's due-date requirement, the MIP considers both customer and supplier flexibility to make the supplier selection decision. The MIP also estimates the profit of the order. If there is any profit, the order will be accepted to be processed by the simulation model (virtual factory). Note, the RCCP and MIP both ignore the stochastic data in the real world. When one order is completed, the simulation model will calculate the real profit. The detail of each model is described next.

The RCCP module evaluates the feasibility of a new incoming order using the Equation (1):

$$F = \sum_{k \in \mathrm{Z}} \left\{ Q_k \times \left[\sum_{i=1}^{I} (A_{ki} \times PT_{i\mathrm{B}}) \right] \right\} \times + Q_{\mathrm{C}} \times \left[\sum_{i=1}^{I} A_{\mathrm{C}i} \times \left(\sum_{w=\mathrm{B}}^{W} PT_{iw} \right) \right] \quad (1)$$

In this research, it is assumed that the bottleneck workstation is known a priori. All accepted orders which have not been completed by the bottleneck workstation will wait in the queue line. When an order from a customer is received, the total production time, F, can be first calculated by Equation (1).

If workstation B is the bottleneck workstation, and Z is the set of accepted orders that have not been processed by the bottleneck workstation, then the first part of Equation (1), calculates the required time before the new received order is processed through the bottleneck workstation. The second part of Equation (1) calculates the total processing time of the new arrival order C after it starts to be processed in the bottleneck workstation. Then the possible earliest due-date can be calculated by

Equation (2):

$$dep = Lmp + F \tag{2}$$

When an order arrives, the RCCP module first calculates the earliest due-date by Equations (1) and (2). If the earliest due-date is later than the accepted due-dates, *dl*, then the order will be rejected. Otherwise, the order is accepted. Then, the supplier and customer flexibility is considered simultaneously to maximize the profit of this order. The estimated production time, *F*, from Equation (1) is one of the inputs to MIP. The other input data includes minimum and maximum accepted due-dates, *de* and *dl*, corresponding unit price, *pe* and *pl*, minimum delivery leadtime and the corresponding expedited delivery penalty Lm_j and α_j, possible minimum leadtime, *Lmp*, the quantity of the order, *Q*, and the production cost per unit for the product, c_i.

To address the problem of pricing to customers, the relationship between due-date and unit price proposed by Zhang and Tseng (2009) is adopted. Their assumption is similar to Moodie and Bobrowski (1999) which is shown in Figure 1. The shape of due-date to price maximum trade-off curve is a straight line. For due-date *d* ($de \leqslant d \leqslant dl$), the unit price, *p*, can be calculated by Equation (3):

$$p = pe - \frac{pe - pl}{dl - de} \times (d - de) \tag{3}$$

For the supplier selection problem, this research adopts the notion of the relationship between leadtime and unit cost in Das and Abdel-Malek (2003). The lateness of supplier *j*, t_j, is calculated by $Lm_j - dr$. If $t_j > 0$, that means the leadtime is shorter than the minimum delivery leadtime. Then the unit cost becomes $m_j(1+t_j\alpha_j)$. On the other hand, if $t_j < 0$, it means the leadtime of the raw material is larger than the minimum delivery leadtime, then the unit cost of the raw material is still m_j.

This research proposes a MIP to maximize the profit of each arrival order. The total profit of the order can be calculated by Equation (4):

$$Z = Q \times \left[p - c - \sum_{j=1}^{J} m_j (1 + t_j \alpha_j) S_j \right] \tag{4}$$

Equation (4) is the objective function of the proposed MIP. The constraints are as follows:

$$de \leqslant d \leqslant dl \tag{5}$$

$$pl \leqslant p \leqslant pe \tag{6}$$

$$Lm_j - dr \leqslant t_j \tag{7}$$

$$dr + F \leqslant d \tag{8}$$

$$Lmp \leqslant dr \tag{9}$$

$$p = pe - \frac{pe - pl}{dl - de} \times (d - de) \tag{10}$$

$$\sum_{j=1}^{J} S_j = 1 \tag{11}$$

$$d, dr \in \text{Integer} \tag{12}$$

$$S_j \in \{0, 1\} \tag{13}$$

$$p, d, dr, t_j \geqslant 0 \tag{14}$$

Equations (5) and (6) ensure that the due-date and the corresponding unit price cannot exceed the range accepted by the customer. Equation (7) calculates the time unit that the delivery date of raw material is earlier than the minimum delivery leadtime of supplier j. Equation (8) states the relationship between due-date to the customer and delivery date to supplier, in which F indicates the total production time of the order. Equation (9) ensures that the delivery date of the raw material cannot be earlier than the possible minimum leadtime. That means that it is impossible for a supplier to deliver the raw material prior. Equation (10) states the relationship between the unit price and the lead time of finished goods. Equation (11) ensures only one supplier is selected. Equation (12) ensures that the due-date of finished goods and raw material are integers. Equation (13) specifies binary variables; and Equation (14) is non-negative constraints.

The MIP solves the optimal unit cost of raw material, unit price of finished goods, p, due-date of finished goods, d, leadtime of the raw material, dr. It also decides which supplier, S_j, to supply the raw material. It assumes that the customers and suppliers will accept the optimal solution as long as it complies with customers and suppliers' flexibility structures. If there is a negative profit, the order is rejected. Otherwise, the order is accepted, and is then further evaluated by the simulation model.

The simulation module is used to evaluate the expected profit at this stage given the inputs – dr and S_j, which are outputs from MIP. The factory will continue its production and is ready for accepting a new order. Thus, it is capable of the rolling-planning decision.

4. Case study

The fishing-net industry has unique characteristics and has not been discussed in the literature with regard to supply network flexibility. Hsieh *et al.* (2012) introduced the fishing-net manufacturing process in detail and then developed a hierarchical RCCP model and demand management system. This section addresses material flow of a fishing-net manufacturing process to show the importance of supply network flexibility.

There are various fishing nets, such as gill nets, lift nets, drag nets, surrounding nets (purse seine nets), set nets (trap nets), covering nets and fish breeding nets. Each net has a unique application which is based on the ocean environment, fish kinds and boat size. Therefore, the same customer could order nets of different types or different sizes.

Each order requires different raw material types, twine sizes, mesh sizes, mesh depths and mesh lengths. The raw material of fishing nets includes polyester, nylon filament and nylon multi-filament. Raw material filaments are twisted into yarn and then twined yarns are produced into strands. Strands are twisted into twine, and then braided twines into rope. Mesh size is a special unit of a net; different mesh depth and mesh length will result in a different shape and area of fishing net. Readers can refer to Hsieh *et al.* (2012) for details. Customers' orders consist of any raw material type, twine size, mesh size, mesh depth and mesh length based on their business needs. Such composition makes size of an order varied and complex.

In the case company there are eight workstations for fishing-net manufacturing as illustrated in Figure 3. They are twisting, braiding, net knitting, dyeing, drying, depthway, lengthways and suture. All manufactured finishing nets follow the sequence of the above workstations except workstation depthway and lengthways. Workstations depthway and lengthways are parallel workstations, and after drying workstation, the fishing nets are directly transported to either one of these two different workstations according to the type of fishing-net. Moreover, for the case company, the net knitting workstation is a bottleneck. For details of each workstation, readers can refer to Hsieh *et al.* (2012).

5. Empirical illustration

This research uses the simulation software Arena® 10.0 published by Rockwell, as a construction tool for the simulation model (Kelton *et al.*, 2007). The simulation software provides a coding tool, visual basic for applications (VBA), for controlling the simulation model. In this research the proposed MIP is developed using Microsoft Excel

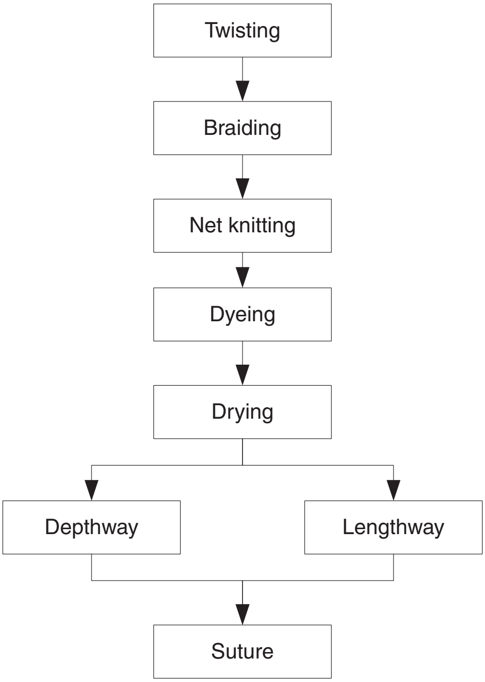


Figure 3.
The fishing-net manufacturing process

Source: Hsieh *et al.* (2012)

Solver which is embedded in the simulation model by using the VBA. When an order is received, Equations (13) and (14) which were coded in the simulation model are first used to evaluate the expected total production time, F, and the earliest due-date. If the order can be completed before the maximum accepted due-dates, dl, then Microsoft Excel Solver will maximize the total profit according to the proposed MIP based on the order-related information. If there is profit, the order will be accepted to enter the manufacturing process. Otherwise the order will be rejected. For all accepted orders, the simulation will evaluate the total profit based on the simulation results.

The simulation model was validated by the case study company. According to the historical data of the case study company, the probability of the required raw materials – polyester, nylon filament and nylon multi-filament – for each order are 21, 51 and 28 percent, respectively. All suppliers are capable of providing those materials. The company receives one order every 12.3 hours on average and the range of weight of each order is between 2,000 and 3,000 kilograms. The processing times of each material type in each workstation are shown in Figure 1. It can be noted that the processing time is based on per 100 kilograms for each material due to the required net sizes of every order being different. The simulation run length is 305 days, with a start-up of 41 days and replications of ten. Based on the case company's order structure, the utilization of the bottleneck workstation (net knitting workstation) is 87.75 percent. The difference between the simulation results and the real situation of case company is 1.98 percent. Accordingly, the simulation model is validated (Table I).

Moreover, in the case company, no accepted order will be delayed. If the order is completed after the maximum accepted due-date, dl, the order will be transported by air. However, using air freight will increase the transportation cost. In this research it is assumed that the air transportation cost is $2.5 \times (p - c - m_j)$. Therefore if an order is completed after the maximum accepted due-date during the simulation run, the simulation model will calculate the transportation cost that is deducted from the resulting profit.

5.1 *Experimental structure*

This research analyses the effect on total profit of scenarios adopting customer flexibility and supplier flexibility. The customer flexibility and supplier flexibility summary is shown in Tables II and III.

In Table II there are three types of customer flexibility, with *ed* indicating the expected due-date by customer. In this research, when an order arrives the anticipated due-date is decided upon, based on uniform (20, 50) days. The *lup* indicates the list unit

			Processing time (minutes/kg)		
No.	Process	Numbers of machine	Polyester	Nylon filament	Nylon multi-filament
1	Twisting	5	0.78	0.78	1.56
2	Braiding	6	1.02	1.02	2.04
3	Net knitting	35	15.00	9.00	4.20
4	Dyeing	1	0.78	0.78	0.78
5	Drying	1	0.12	0.12	0.12
6	Depthway	4	0.12	0.18	0.12
7	Lengthway	4	0.06	0.18	0.12
8	Suture	50	3.84	3.84	3.84

Table I.
The machine data

price based on the type of fishing net. Where strategy C_0 is deployed, it indicates that customers have no flexibility in both unit price and due-date. For types C_1 and C_2, customers provide flexibility in both due-date and unit price. It can be noted that in strategy C_1, the flexible range between earliest and latest due-date is higher than strategy C_2, but the range of unit price between earliest and latest due-date is smaller than C_2. It means that customers in type C_1 provide higher due-date flexibility and the customers in type C_2 provide higher price flexibility.

There are two suppliers for the case company; and as shown in Table III, there are three types for supplier flexibility. For type S_0, the minimum delivery leadtime and the corresponding expedited delivery penalties of both suppliers are the same. But the minimum delivery leadtimes are longer and the expedited delivery penalties are smaller than types S_1 and S_2. With regard to types S_1 and S_2, both suppliers provide different flexibility with minimum delivery leadtimes and the corresponding expedited delivery penalties. However, it can be noted that the difference between the flexibility provided by the two suppliers in type S_1 is higher than type S_2.

The experimental scenarios are considered under two factors: order interarrival time and order quantity. The factor levels are shown in Tables IV and V. There are three levels for order interarrival time and five levels for order quantity. Thus there are, in total, 15 experimental scenarios.

5.2 *Experimental results analysis*

There are three types of customer flexibility and three types of supplier flexibility; thus there are in total nine combinatorial flexibility types. The experimental results are shown in Table VI.

Table II.
The types of customer flexibility

	Flexibility parameters	
Type	(de, dl)	(pl, pe)
C_0	(ed, ed)	(lup, lup)
C_1	$(ed-5$ days, $ed+5$ days)	$(lup-4$ dollars, $lup+4$ dollars)
C_2	$(ed-3$ days, $ed+3$ days)	$(lup-7$ dollars, $lup+7$ dollars)

Table III.
The types of supplier flexibility

	Flexibility parameters			
	Supplier 1		Supplier 2	
Type	Lm_1 (days)	α_1 (%)	Lm_2 (days)	α_2 (%)
S_0	9	3	9	3
S_1	4	12	7	8
S_2	6	7	8	5

Table IV.
Scenario factors of interarrival time

Factor levels	Interarrival time (hour)
Level 1 (A_1)	Exp. (10.6)
Level 2 (A_2)	Exp. (12.3)
Level 3 (A_3)	Exp. (16.0)

In Table VI, it is seen that when flexibility in both unit price and due-date are not accepted by the customer (C_0S_0, C_0S_1 and C_0S_2) it results in lower profits. Moreover, when the interarrival time of the order is long (scenarios A_3O_1, A_3O_2, A_3O_3, A_3O_4 and A_3O_5), it also results in lower profit. It is also noted that for each scenario, when combinatorial flexibility type C_2S_1 is adopted (customers' provide higher unit price flexibility and the suppliers' provide quite different flexibility with minimum delivery leadtimes that attract corresponding expedited delivery penalties), this results in the highest profit. This can be explained by customers providing maximum due-date flexibility, and thus increasing the probability of accepting the order. But if the corresponding unit price flexibility is smaller, the range of increasing profit will be limited. On the other hand, if a customer provides reduced due-date flexibility, but also provides a larger range in unit price flexibility, it would increase profit. Moreover, when the suppliers provide flexibility in minimum delivery leadtimes and the corresponding expedited delivery penalties, the manufacturer can select the supplier who provides highest flexibility to increase the probability of accepting an order and increasing profit. Therefore, it can be inferred that by having customer flexibility and supplier flexibility, simultaneously, profits will be maximized.

In Table VI it is also found that the average profit of C_0S_1 is higher than C_0S_0 and C_0S_2; C_1S_1 is higher than C_1S_0 and C_1S_2; C_2S_1 is higher than C_2S_0 and C_2S_2. It means that no matter the flexibility of a customer, when the supplier flexibility is type S_1, a higher profit can result. This finding suggests that the manufacturers should develop suppliers who provide different flexibility. Additionally, it can be found that the average profit of C_2S_0 is higher than C_1S_0 and C_0S_0; C_2S_1 is higher than C_1S_1 and C_0S_1; C_2S_2 is higher than C_1S_2 and C_0S_2. It means that no matter the extent of supplier flexibility, when the customer flexibility is type C_2, higher profit can result. This finding suggests that the manufacturers should increase price flexibility rather than due-date flexibility when developing contracts with customers.

5.3 Sensitivity analysis

For each type of flexibility, both suppliers provide minimum delivery leadtimes and the corresponding expedited delivery penalty (see Table III). For strategy S_0, the flexibility of both suppliers is the same. This research sets the minimum delivery leadtime as nine days, and changes the corresponding expedited delivery penalty from 0 to 5 percent to test strategy C_0S_0. The differences between delivery penalty 0-4 percent and 5 percent are shown in Figure 4.

When the expedited delivery penalty is 0 percent, it indicates that the suppliers provide the highest flexibility. The suppliers can deliver the raw material without any extra charge – even when the delivery lead time is close to 0. In Figure 4, it can be seen that the higher expedited delivery penalty results in the lower total profit. It is also found that the total profit will not continue decreasing when the expedited delivery penalty is greater

Factor levels	Order quantity (kg)	Mean	SD
Level 1 (O_1)	Unif. (1,750, 2,750)	2,250	228
Level 2 (O_2)	Unif. (2,000, 3,000)	2,500	228
Level 3 (O_3)	Unif. (2,250, 3,250)	2,750	228
Level 4 (O_4)	Unif. (2,250, 2,750)	2,500	144
Level 5 (O_5)	Unif. (1,500, 3,500)	2,500	577

Table V.
Scenario factors of order quantity

Table VI.
The experimental results

	Strategies								
Scenario	C_0S_0 (\$)	C_1S_0 (\$)	C_2S_0 (\$)	C_0S_1 (\$)	C_0S_2 (\$)	C_1S_1 (\$)	C_1S_2 (\$)	C_2S_1 (\$)	C_2S_2 (\$)
A_1O_1	1,077,577	1,227,540	1,241,626	1,126,510	1,071,650	1,295,547	1,233,537	1,375,688	1,309,290
A_1O_2	1,092,810	1,168,214	1,256,286	1,135,216	1,100,651	1,255,138	1,214,064	1,423,130	1,306,274
A_1O_3	1,089,252	1,104,184	1,152,586	1,168,984	1,114,509	1,256,335	1,182,961	1,337,188	1,310,980
A_1O_4	1,128,808	1,221,164	1,222,257	1,172,764	1,105,269	1,315,541	1,240,070	1,406,312	1,341,056
A_1O_5	1,080,653	1,196,418	1,199,114	1,160,037	1,086,333	1,276,489	1,227,546	1,338,702	1,291,836
A_2O_1	976,118	1,178,431	1,175,918	1,028,489	979,143	1,205,308	1,174,654	1,275,517	1,204,313
A_2O_2	1,022,557	1,192,302	1,206,642	1,053,016	1,018,931	1,255,076	1,224,256	1,321,499	1,271,228
A_2O_3	1,032,804	1,167,676	1,175,671	1,088,815	1,017,642	1,248,900	1,198,134	1,342,471	1,290,078
A_2O_4	1,022,612	1,189,694	1,223,131	1,059,374	1,003,275	1,235,697	1,220,003	1,332,501	1,296,796
A_2O_5	1,029,453	1,205,111	1,168,341	1,069,341	1,008,770	1,203,780	1,177,195	1,300,171	1,243,285
A_3O_1	788,521	937,419	964,366	813,727	787,943	952,133	930,600	1,004,042	989,428
A_3O_2	849,252	986,054	1,047,555	856,431	840,935	1,026,229	992,337	1,106,384	1,056,950
A_3O_3	870,736	1,007,550	1,079,504	923,239	863,117	1,119,054	1,070,319	1,145,289	1,071,540
A_3O_4	847,376	1,004,034	1,007,923	862,634	844,506	1,010,012	1,049,175	1,102,548	1,059,123
A_3O_5	847,681	1,014,402	1,006,609	838,870	810,250	982,772	998,147	1,057,763	1,012,113
Average	983,747	1,120,013	1,141,835	1,023,830	976,862	1,175,868	1,142,200	1,257,947	1,203,619

than 4 percent. That indicates that in the combinatorial flexibility type C_0S_0, the suppliers can be viewed as having "no flexibility" when the expedited delivery penalty is greater than 4 percent. This research then compares the results of combinatorial flexibility type C_0S_0, whose expedited delivery penalty is 5 percent, with the results shown in Table VI. The improvements resulting from the strategies that have a certain level of flexibility (in Table VI) compared to the strategy with no flexibility are shown in Figure 5.

In Figure 5 it shows that all flexible types outperform the non-flexible types. For combinatorial flexibility type C_0S_0, C_0S_1 and C_0S_2 where only supplier flexibility is provided, the improvements are quite small. However, among the three combinatorial flexibility types, the C_0S_1 results in the greater improvement in almost all the scenarios – since there is one supplier: S_1, who provides the shortest minimum delivery leadtime. For emergency orders, the producer will choose the supplier with no penalty if the leadtime of the raw material is longer than the shortest minimum delivery leadtime. In Figure 5 it can also be found that when both suppliers and customers provide flexibility simultaneously, it results in higher improvements. In particular, when both suppliers and customers provide the highest flexibility simultaneously (combinatorial flexibility type C_2S_1) it results in the most improvement.

Moreover, in Figure 5, there is an improvement gap between combinatorial flexibility types as demand rate increases (A_2 and A_3). The combinatorial flexibility

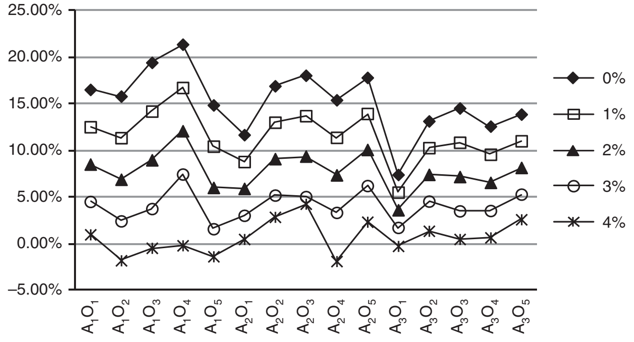


Figure 4.
The change of profit with different expedited delivery penalties

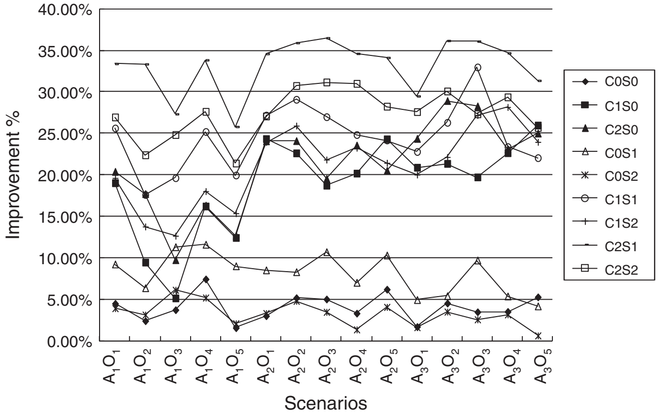


Figure 5.
The improvement of flexible strategies

types under the gap are C_0S_0, C_0S_1 and C_0S_2. That means that when demand rate is increasing, the more flexibility provided by customers, the greater the profit improvement will be.

6. Conclusions and future research

In a MTO production system, manufacturers do not hold inventory of finished goods to immediately satisfy customers' demand. Similarly, when manufacturers do not hold a raw material inventory they are at risk of delaying production while waiting on new supplies. If customers or suppliers can provide flexibility, for example customers can accept a later due-date with an increased unit price or the suppliers can deliver the raw material earlier with an extra charge, then manufacturers would have more chance to accept orders from customers and achieve increased total profit. In this research several flexibility types were tested where delivery leadtime and unit price (or raw material cost) could be negotiated with customers and suppliers. A MIP was developed for determining the optimal raw material delivery date, the raw material cost, due-date of finished goods and unit price of finished goods to maximize the total profit. Moreover, in order to reflect the stochastic nature of real-world problems, the MIP is embedded in a simulation model. When an order is received, if the results of the MIP show that there is a profit, the simulation model will evaluate the total profit by taking the stochastic factors into consideration. The experimental results show that when either customers or suppliers provide flexibility it can increase the total profit. Significantly, it shows that customers who provide best flexibility with price can result in higher profits than customers who provide best flexibility with due-date. Moreover, developing suppliers to provide a wide range of flexibility in both due-date and price can also increase the total profit. However, the generalizability of these results to production strategies beyond those described in this research should be heeded with caution. The results from this specific case scenario give rise to a belief that the work has wider implications; but this assumption requires future testing.

The experimental results also show that if only supplier flexibility is developed, the manufacturers should source suppliers who provide quite different flexibility. As regards customer flexibility, if only price flexibility and due-date flexibility can be negotiated with customers then the results suggest that the price flexibility has greater importance. Although the conclusion is based on the experimental results of a case company, we suggest that this supply chain strategy can be suitable for other MTO companies.

The range of flexibility of both customer and supplier is small, although the experimental results show that the flexibility has a positive impact on the profit. An expanded experiment would be of help in realizing the relationship between the flexibility and the profit. Moreover, there are other price-sensitivity functions for both customers and suppliers that should be explored. The present study only uses leadtime as the performance measure and assumes that the price is a linear function of the delivery leadtime. This assumption is, arguably, simplistic when there are other significant price factors in some instances. There are some factors that can be taken into consideration for measuring the flexibility of suppliers and customers, such as quality (Liao and Rittscher, 2007b) and order quantity (Liao and Rittscher, 2007a) and product attributes (Zhang and Tseng, 2009). Accordingly, it is a future research opportunity to develop a more extensive model that will consider more flexibility factors (in addition to due-date and unit price). The current research represents a logical progression from the extant literature (Zhang and Tseng, 2009), with results clearly indicating useful findings.

This research aims at solving a specific and unique application which is not addressed in the literature. Thus, it has built an application for a specific simulation model which is then validated by a real-world application. The managerial insights gained from the present study are strategically important for the case company in developing the integration of a customer and supplier flexibility strategy. The results also have wider implications for similar MTO producers. Analyzing the influence of different combinations of customers' and suppliers' flexibility structures to other manufacturing processes would also offer the opportunity of future research. Moreover, the logistics or distribution design plays an importation role in the effectiveness of the supply chain. If a MTO's faster delivery is enabled by shortened flow times, then its lower work-in-process inventories and inventory carrying costs may provide another competitive advantage (Easton and Moodie, 1999). Based on the degree of integration of customer and supplier flexibility, the efficiency of the distribution system can be improved and the transportation lead time can then be reduced. Thus the frequency of new orders can be increased and the due-date can be advanced to increase the price and profit.

While the conclusions indicate significant improvements to the case organization, clearly to identify more generic improvements across differing production strategies, the model should embrace alternative situations. For example, Xu *et al.* (2009) identified considerable economic benefits to be afforded by supplier integration, lean production philosophy and just-in-time methods. While a considerable challenge, such modes of operations should be addressed in future research.

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Corresponding author
Professor Taho Yang can be contacted at: tyang@mail.ncku.edu.tw