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An integrated operations-marketing perspective for making decisions about order penetration point in multi-product supply chain: a queuing approach

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This study is dedicated to strategic decision-making regarding order penetration point (OPP), which is the boundary between make-to-order (MTO) and make-to-stock (MTS) policies. This paper considers a supply chain in which a manufacturer produces semi-finished items on an MTS basis for a retailer that will customise the items based on MTO policy. This two-echelon supply chain offers different products to a market comprised of homogenous customers who have different preferences and willingness to pay. The retailer wishes to determine the optimal OPP, the optimal semi-finished goods buffer size, and the price of the products with assumption of price sensitive demand function. Moreover, we consider both shared and unshared capacity models in this paper. A matrix geometric method is utilised to evaluate various performance measures for this system, and then, optimal solutions are obtained by enumeration techniques. The suggested queuing approach is based on a new perspective between the operations and marketing functions which captures the interactions between several factors including inventory level, product pricing, OPP, and delivery lead time. Finally, parameter sensitivity analyses are carried out and the effect of demand on the profit function, the effect of prices ratio on completion rates ratio and buffer sizes ratio and the variations of profit function for different prices, completion percents, and buffer sizes are examined.

Keywords: queuing system; supply chain; order penetration point (OPP); integrated operations-marketing perspective; MTS-MTO queue; matrix geometric method (MGM)

1. Introduction

One production system which has recently attracted researchers' and practitioners' consideration is hybrid make-to-order/ make-to-stock (MTS-MTO) (Rafiei and Rabbani 2012). The MTS production system can meet customer orders fast, but confronts inventory risks associated with short product life cycles and unpredictable demands. In contrast, MTO producers can provide a variety of products and custom orders with lower inventory risks at the expense of longer customer lead times. Moreover, in MTS production, products are stocked in advance, while in MTO, a product starts to be produced only after an order is received. The MTS-MTO supply chain is appropriate wherever common modules are shared by various finished products through divergent finalisation. The MTS-MTO supply chain inherits two key characteristics: First, it can reduce cost of producing standard modules by taking advantage of economies of scale during the MTS stage. Second, it can concurrently satisfy the need for high product variety by taking advantage of MTO's flexibility (Wang et al. 2011). To differentiate the three above-mentioned systems, the concept of Order Penetration Point (OPP) is utilised in Figure 1. This point specifies the stage where the customer's desired specifications influences the production value chain (Hoekstra, Romme, and Argelo 1992). As shown in Figure 1, customer's specifications are taken into consideration in different places along the production systems in MTS, MTO and MTS-MTO.

Delayed product differentiation (DPD) is a common concept in supply chain management in which the manufacturing process starts by making a generic or family product that is later differentiated into a specific end-product. This method is widely used, especially in industries with high demand uncertainty, and can be effectively used to address the final demand even if anticipations cannot be improved. DPD leads to improved customer satisfaction and manufacturing performance through balancing various costs pertaining to different products with different specifications. Besides, as stated by Jewkes and Alfa (2009), DPD can increase a manufacturer's flexibility to deal with uncertainties in market demand. It can be achieved by, for instance, component sharing or reversing the order of operations, as discussed by Lee and Tang (1997). The benefits of DPD as claimed by Jewkes and Alfa (2009) consist of an ability to provide

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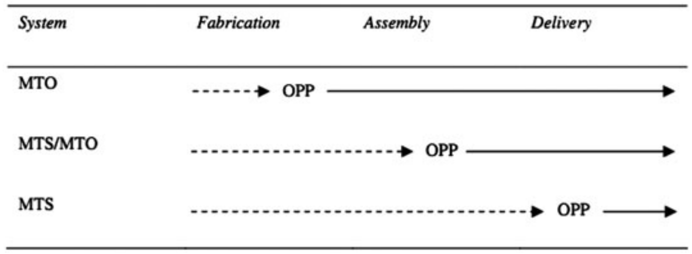

Figure 1. Different production systems; dotted and solid lines represent forecast-driven and customer-order-driven activities, respectively.

custom products with lower customer order fulfilment delay compared to pure MTO systems' delay, and, due to inventory pooling, the ability to hold less overall inventory than MTO systems. The drawbacks of DPD include the potential for increased costs (due to additional material or processing costs), and the risk of greater yield losses or expenditures of process redesign. Another risk of DPD is pertained to the product market – it may become more difficult to respond to the full range of final product specifications demanded by customers.

The positioning of OPP is a challenging area that has received an increasing attention in the manufacturing strategy literature (Hallgren and Olhager 2006). As mentioned in Figure 1, OPP is taken into consideration in different locations along the production systems in MTS, MTO and MTS-MTO. Accordingly, we consider three environments MTS, MTO and MTS-MTO for positioning OPP in supply chain networks as the analysis of the problem is different for each environment. By bringing Table 1, we prefer to display a general overview of our developed OPP models for readers in this section. As shown in Table 1, our developed OPP models in Teimoury et al. (2010), Teimoury et al. (2011) and (Teimoury et al. 2012; Teimoury and Fathi 2012; current research) are in MTS, MTO, and MTS-MTO environment, respectively.

The motivation for this study is that companies are showing an increasing interest in incorporating the OPP as an important input into the strategic design of supply chains. Moreover, making decisions on the price of products in a supply chain with a price sensitive demand function is considered as strategic decision-making with respect to location of the OPP. In practical supply chain management, financial aspects such as the price of a finished product, which has a direct relationship with customer satisfaction, play a vital role. This decision making is affected by different factors such as supply chain configuration and structure, and delivery lead-time. Therefore, we believe that the integrated operations-marketing perspective is needed in positioning OPP in supply chain networks. The rest of the paper is organised as follows. The corresponding literature is reviewed in the next section. The problem description and list of notation are explained in Section 3. The model formulation is studied under shared and unshared inventory capacity in Section 4. Moreover, the queuing aspect and performance evaluation indices are studied. Section 5 is dedicated to a two products supply chain numerical example. And finally, the study is concluded in Section 6.

2. Literature review

There are a number of papers addressing the issue of making decisions on OPP, which has appeared in the literature with various names, such as decoupling point (DP), DPD and product customization postponement. The term DP, in the logistics framework was first introduced by Sharman (1984) where he argued the DP's dependency on a balance between product cost, competitive pressure and complexity.

Positioning OPP includes MTS or MTO decision or hybrid MTS-MTO decision making. According to Shao and Dong (2012) the selection between MTS and MTO is an important decision in many industries, such as contract manufacturers Kumar et al. (2007), plastic toy manufacturing firms Rajagopalan (2002), food companies (Van Donk 2001; Soman, Van Donk, and Gaalman 2004; Akkerman, Van der Meer, and Van Donk 2010), steel mills Kerkkänen 2007, semiconductor plants Chang et al. (2003), timber industry Yáñez et al. (2009) and personal computer manufacturing firms Vidyarthi, Elhedhli, and Jewkes (2009). There is also a large amount of literature explicitly dealing with the hybrid MTO–MTS problem (Sox, Thomas, and McClain 1997; Carr and Duenyas 2000; Soman, Van Donk, and Gaalman 2004; Hallgren and Olhager 2006; Perona, Saccani, and Zanoni 2009; Jewkes and Alfa 2009; Teimoury et al. 2012; Teimoury and Fathi 2012). A comprehensive literature review on MTS-MTO production systems and revenue management of demand fulfilment can be found in Perona, Saccani, and Zanoni (2009) and Quante, Meyr, and Fleischmann (2009).

Table 1. Details of our developed OPP models.

Authors	Problem	Supply chain environment	Demand	Customer type	OPP	Modelling method	Research questions
Teimoury et al. (2010)	A queuing approach to production-inventory planning for supply chain with uncertain demands: Case study of PAKSHOO Chemicals Company	MTS	Poisson process	Multi classes	Located at the end of supply chain network	Stochastic modelling and optimisation, queuing and Markov chain modelling	How can the operational decisions of production-inventory planning be optimised simultaneously in the MTS supply chain environment?Can queuing approach be applied to model uncertainty in demand and delivery time in MTS environment?
Teimoury et al. (2011)	Price, delivery time, and capacity decisions in an M/M/1 make-to-order/service system with segmented market	MTO	Price and delivery lead-time sensitive demand function	Two classes	Located in front of supply chain network		Can queuing approach be applied to model uncertainty in demand and delivery time in MTO environment? According to delivery lead-time and price sensitive demand function of customers in MTO environment, how queuing approach can be applied to optimise price, delivery lead-time and capacity?
Teimoury et al. (2012)	A queuing approach for making decisions about order penetration point in multi-echelon supply chains	MTS-MTO	Poisson process	Multi classes	Decision variable		Can queuing approach be applied to determine the OPP of a multi-product supply chain in MTS-MTO environment? How stochastic modelling and optimisation is proportional to the structure of positioning OPP under uncertain demand and the delivery time? How can the logistics process and transportation mode of finished products to the customers in determining OPP be optimised?
Teimoury and Fathi (2012)	A queuing approach for making decisions about order penetration point in supply chain with impatient customer	MTS-MTO	Poisson process	Single class, impatient customer	Decision variable		Can queuing approach be applied to determine the OPP of a supply chain with impatient customers in MTS-MTO environment?How stochastic modelling and optimization is proportional to the structure of positioning OPP under uncertain demand and the delivery time with impatient customers?Is considering impatient customer important in determining OPP in MTS-MTO environment?

(*Continued*)

Table 1. (*Continued*).

Authors	Problem	Supply chain environment	Demand	Customer type	OPP	Modelling method	Research questions
Current research	An integrated operations-marketing perspective for making decisions about order penetration point in multi-product supply chain: A queuing approach	MTS-MTO	Price sensitive demand function	Multi classes	Decision variable		Can queuing approach be applied to determine the OPP of a multi-product supply chain with an integrated operations-marketing perspective in MTS-MTO environment?How stochastic modelling and optimisation is proportional to the structure of positioning OPP under uncertain demand and the delivery time with an integrated operations-marketing perspective?How can OPP be determined based on an integrated operations-marketing perspective with the assumption of price sensitive demand function?

Adan and Van der Wal (1998) studied the effect of MTS and MTO production policies on order satisfaction lead-times. Arreola-Risa and DeCroix (1998) analysed the effect of manufacturing-time diversity on MTO/MTS decisions and presented optimality conditions for MTO/MTS partitioning in a multi-product, single-machine case with an FCFS scheduling rule. Their results showed the extent to which reducing manufacturing-time randomness leads to MTO production. Recently, Günalay (2011) studied the efficient management of MTS or MTO production-inventory system in a multi-item manufacturing facility. Rajagopalan (2002) proposed a model and a solution approach for deciding whether a set of items should be MTS or MTO and the production policy for the MTS items. The objective of his model was to minimise inventory costs of MTS items while ensuring that orders for MTO items were satisfied within a lead time, T, with a specified probability. Su et al. (2010) analysed the cost and benefit of implementing DPD in an MTO environment (in the Hewlett-Packard printer case, printers were made in an MTS environment) by means of queuing models.

The trade-off between aggregation of inventory (or inventory pooling) and the costs of redesigning the production process is studied by Aviv and Federgruen (2001) where congestion impacts are not taken into account. In contrast, Gupta and Benjaafar (2004) included the impact of capacity restrictions and congestion, i.e. they proposed a common framework to examine MTO, MTS and DPD systems in which production capability is considered. Furthermore, they analysed the optimal postponement point in a multi-stage queuing system. The DPD issue in manufacturing systems is studied by Jewkes and Alfa (2009) in which they decided on where to locate the point of differentiation in a manufacturing system, and also what size of semi-finished products inventory storage should be considered. In addition, they presented a model to realise how the degree of DPD affects the trade-off between customer order completion postponement and inventory risks, when both stages of production have non-negligible time and the production capacity is limited. Their model did not, however, consider the demand to be a function of price. In this paper, we extend their model for multi-product supply chain under shared and unshared inventory capacity and consider the demand to be a function of price products. Such an extension is useful in viewing the problem in an integrated operations-marketing perspective which is more practical for managers.

Recently, Ahmadi and Teimouri (2008) studied the problem of where to locate the OPP in an Auto Export supply chain by means of dynamic programming. Teimoury et al. (2010) proposed an integrated two stage inventory-queue model and production planning model based on queuing approach in real case study of PAKSHOO chemicals company uncertain demands. Teimoury and Fathi (2012) developed a queuing model for locating OPP in a two-echelon supply chain with impatient customers. While Teimoury et al. (2012) proposed a queuing model for making decisions about OPP in multi-echelon supply chains, they did not discuss in an integrated operations-marketing framework. Furthermore, a notable literature review in positioning DPs and multiple DPs in a supply network can be seen in Sun et al. (2008); these positioning models did not, however, make any decisions about the optimal semi-finished buffer size and optimal fraction of processing time fulfilled by the upstream of DP. Wong, Wikner, and Naim (2009) studied postponement based on the positioning of the differentiation points and the stocking policy. Wee and Dada (2010) studied a make-to-stock manufacturing system with component commonality based on queuing approach. Jeong (2011) developed a dynamic model to simultaneously determine the optimal position of the decoupling point and production–inventory plan in a supply chain.

This paper investigates an integrated operations-marketing perspective based on queuing approach for making decisions about OPP in supply chain. A comprehensive review of operations-marketing interface models is studied by Tang (2010) and many applications and methods of operations-marketing perspective are surveyed in O'Leary-Kelly and Flores (2002), Ho and Zheng (2004), Ray (2005), Feng, D'Amours, and Beauregard (2008), Ioannidis and Kouikoglou (2008), Rao (2009), Vandaele and Perdu (2010), Feng, D'Amours, and Beauregard (2010), Erickson (2011), Oliva and Watson (2011), Wong and Eyers (2011) and Chayet, Hopp, and Xu (2004). Many applications and methods for determining the OPP are also presented in Olhager (2003, 2010), Yang and Burns (2003), Mikkola and Skjøtt-Larsen (2004), Yang, Burns, and Backhouse (2004), Rudberg and Wikner (2004), Wikner and Rudberg (2005), Skipworth and Harrison (2004, 2006), Harrison and Skipworth (2008), Wong, Wikner, and Naim (2009), Banerjee, Sarkar, and Mukhopadhyay 2012, and Choi, Narasimhan, and Kim (2012). Moreover, following authors have developed their models based on queuing approach (Arreola-Risa and DeCroix 1998; Gupta and Benjaafar 2004; Wong, Wikner, and Naim 2009; Jewkes and Alfa 2009; Wee and Dada 2010; Su et al. 2010; Wong, Wikner, and Naim 2010; Teimoury et al. 2010; Wong and Eyers 2011; Teimoury et al. 2011; Teimoury et al. 2012; Teimoury and Fathi 2012). According to Table 2, we are the authors of five papers out of 13 available papers in the literature and current work is based on highlighted papers in Table 2 which are mostly related to the literature of our study.

For the first time, current research based on queuing approach considers pricing decisions, determining decoupling point and warehouse capacity planning, simultaneously. Having added the pricing decision and assumption of price sensitive demand function to the developed model by Teimoury et al. (2012), the proposed model improves the OPP model and makes it more realistic and applicable to real cases. The mathematical models in OPP literature commonly seek a

Table 2. Literature review of developed OPP models based on queuing approach.

Authors	Problem	Published journal
Arreola-Risa and DeCroix (1998)	Make-to-order versus make-to-stock in a production–inventory system with general production times	*IIE Transactions*
Gupta and Benjaafar (2004)	Make-to-order, make-to-stock, or delay product differentiation? A common framework for modelling and analysis.	*IIE Transactions*
Wong, Wikner, and Naim (2009)	Analysis of form postponement based on optimal positioning of the differentiation point and stocking decisions	*International Journal of Production Research*
Jewkes and Alfa (2009)	A queuing model of delayed product differentiation	*European Journal of Operational Research*
Wee and Dada (2010)	A make-to-stock manufacturing system with component commonality: A queuing approach	*IIE Transactions*
Su et al. (2010)	The impact of delayed differentiation in make-to-order environments	*International Journal of Production Research*
Wong, Wikner, and Naim (2010)	Evaluation of postponement in manufacturing systems with non-negligible changeover times	*Production Planning & Control*
Wong and Eyers (2011)	An analytical framework for evaluating the value of enhanced customisation: an integrated operations-marketing perspective.	*International Journal of Production Research*
Teimoury et al. (2010)	A queuing approach to production-inventory planning for supply chain with uncertain demands: Case study of PAKSHOO Chemicals Company	*Journal of Manufacturing Systems*
Teimoury et al. (2011)	Price, delivery time, and capacity decisions in an M/M/1 make-to-order/service system with segmented market	*International Journal of Advanced Manufacturing Technology*
Teimoury et al. (2012)	A queuing approach for making decisions about order penetration point in multi-echelon supply chains	*International Journal of Advanced Manufacturing Technology*
Teimoury and Fathi (2012)	A queuing approach for making decisions about order penetration point in supply chain with impatient customer	*International Journal of Advanced Manufacturing Technology*
Current research	An integrated operations-marketing perspective for making decisions about order penetration point in multi-product supply chain: A queuing approach	*International Journal of Production Research*

balance between inventory costs and customer service levels, but to the authors' knowledge, pricing problem in OPP positioning has not been noticed in literature nonetheless. The proposed queuing approach is based on a new perspective between the operations and marketing functions which captures the interactions between several factors including inventory level, price, OPP, and delivery lead time. Moreover, the proposed model attempts to maximise the revenue of the supply chain. Therefore, the model should optimise the price of each product type which results in an integrated operations-marketing interface perspective which has become more practical and more comprehendible to supply chain managers.

The goal of this paper is to find equilibrium customer service levels with inventory costs, as akin to developed models in the literature as in Teimoury et al. (2010, 2011, 2012), Teimoury and Fathi (2012) and Jewkes and Alfa (2009). Ours, however, differs from the studied articles in several ways. First, pricing decision making is added to the OPP model as a decision variable. Second, the literature chiefly focuses on single product modelling. On the contrary, the developed model covers multi-product supply chains. Third, in contrast to the previous studies in literature, we assume, for the first time, a price sensitive demand function in our OPP positioning model and demand function is considered to be a function of prices of different products which are replaceable. Finally, in this study, there are: practical base; integrating operations-marketing perspective by adding decision on product pricing with assumption of price sensitive demand function and theoretical base; applying queuing approach for modelling the problem because of uncertain nature of demand arrival and lead-time. Therefore, this model optimises both marketing and operations simultaneously to obtain OPP in supply chain networks and our point of view to the problem helps our previous OPP positioning models to get closer to practical models in real cases.

The supply chain which is considered as a basic model in this paper is composed of two production stages. In the first production stage, the manufacturer produces semi-finished products on an MTS policy for a retailer in the second production stage that will customise the products based on an MTO policy. The semi-finished products will be completed as a result of specific customer orders. The developed model obtains the optimal prices of the products for the completed products to each demand point. In order to balance the costs of customer order fulfilment delay and inventory costs of each product type, retailer tries to find the optimal fraction of processing performed by the manufacturer and its optimal semi-finished products buffer storage.

3. Problem description and list of notation

The following notations are used for the integrated operations-marketing mathematical formulation of the proposed model.

Sets and indices:

m_i	Semi-finished products buffer storage capacity for product of type i index $m_i = 1, 2, ..., S_i$
i	Product's type index i = 1, 2, … , L

Decision variables:

θ_i	Percent of completion for product of type i in the first production stage
S_i	Storage capacity of type i semi-finished products
P_i	Price quoted to product of type i

Parameters:

$V(\theta_i)$	The value per unit of semi-finished products (dollar/unit)
τ_i	Constant fraction of the MTO processing rate for product of type i
μ_i	Mean production rate for product of type i
C_{H_i}	The holding cost for semi-finished product of type i (dollar/unit)
C_{W_i}	The cost of customer order fulfilment delay for product of type i (dollar/unit)
C_{C_i}	The cost of establishing type i semi-finished products storage capacity (dollar/unit)
C_{u_i}	The cost of disposing an unsuitable item of type i (dollar/unit)
λ_i	Mean arrival rate for product of type i

Expected performance measures:

$E(N_i)$	The expected number of type i semi-finished products in the system
$E(W_i)$	The expected customer order completion delay for product of type i – the time from when a customer order enters the system until its product is completed
$E(U_i)$	The expected number of type i unsuitable products produced per unit time

A production supply chain is considered in which a manufacturer produces semi-finished items on a MTS basis for a retailer as shown in Figure 1. Customer orders for completed products arrive at the retailer and are filled on a MTO basis by customising the semi-finished goods to customer specifications. It is assumed that the studied supply chain offers L products to a market comprising homogenous customers that differ in their preferences for willingness to pay. It is considered that a retailer is dealing with multiple types of customers who have different Poisson demand rate and are sensitive to price of the requested product and other products in the line. The demands are differentiated based on the products. According to Tsay and Agrawal (2000), Boyaci and Ray (2007) and Teimoury et al. (2011), the demand rates are modelled using the linear functions $\lambda_i = \alpha_i - \beta_i P_i + \sum_{j \neq i}^{L} \gamma_{ij} P_j$. The demands for a two-product supply chain are as follows:

$$\lambda_1 = \alpha_1 - \beta_1 P_1 + \gamma_1 P_2 \tag{1}$$

$$\lambda_2 = \alpha_2 - \beta_2 P_2 + \gamma_2 P_1 \tag{2}$$

The proposed model seeks to maximise the revenue of the supply chain. Therefore, the model should optimise the price of each product type and this makes an integrated operations-marketing interface perspective.

In this system, customers arrive at random times and each customer requests one unit of a product. The times between successive customer arrivals are independent random variables with rate λ in accordance to a Poisson process. It is assumed that each customer orders one unit of type-i product with a probability of q_i where $\sum_{i=1}^{L} q_i = 1$ and $\lambda_i = \lambda q_i$, $i = 1, 2, ..., L$. The production times of work stations for all product types are assumed to be exponentially distributed with rates μ_i, $i = 1, 2, ..., L$ where $\sum_{i=1}^{L} \mu_i = \mu$. Moreover, it is supposed that the manufacturer has an infinite source of raw materials and never faces shortage. The second production stage has to determine the optimal storage capacity of type i semi-finished products (S_i, $i = 1, 2, ..., L$). Figure 2a and Figure 2b illustrate a diagram depicting the model under both shared (Section 4.1) and unshared (Section 4.2) capacity models, respectively.

As shown in Figure 2, the manufacturer provides undifferentiated semi-finished products to the final production stage. For each product type, manufacturer produces a semi-finished product ($\%100\theta_i$ completed $(0 < \theta_i < 1)$) to be delivered to the final production stage. The final production stage then completes the remaining $1 - \theta_i$ fraction according to a particular customer order. It should be noted that the manufacturer is not necessarily in a different organisation from the retailer; the 'manufacturer' and 'final production stage' may be two successive stages in a same organisation. We modelled θ_i as a continuous variable in order to gain profound insights into the overall relationship between θ_i and the performance of the system. The assumption also facilitates our computational analysis. Therefore, the results is presented as if the final production stage can implement any values of θ_i. If this is not the case, our model enables us to quickly identify the best choice of θ_i among a finite number of feasible alternatives. According to market characteristics

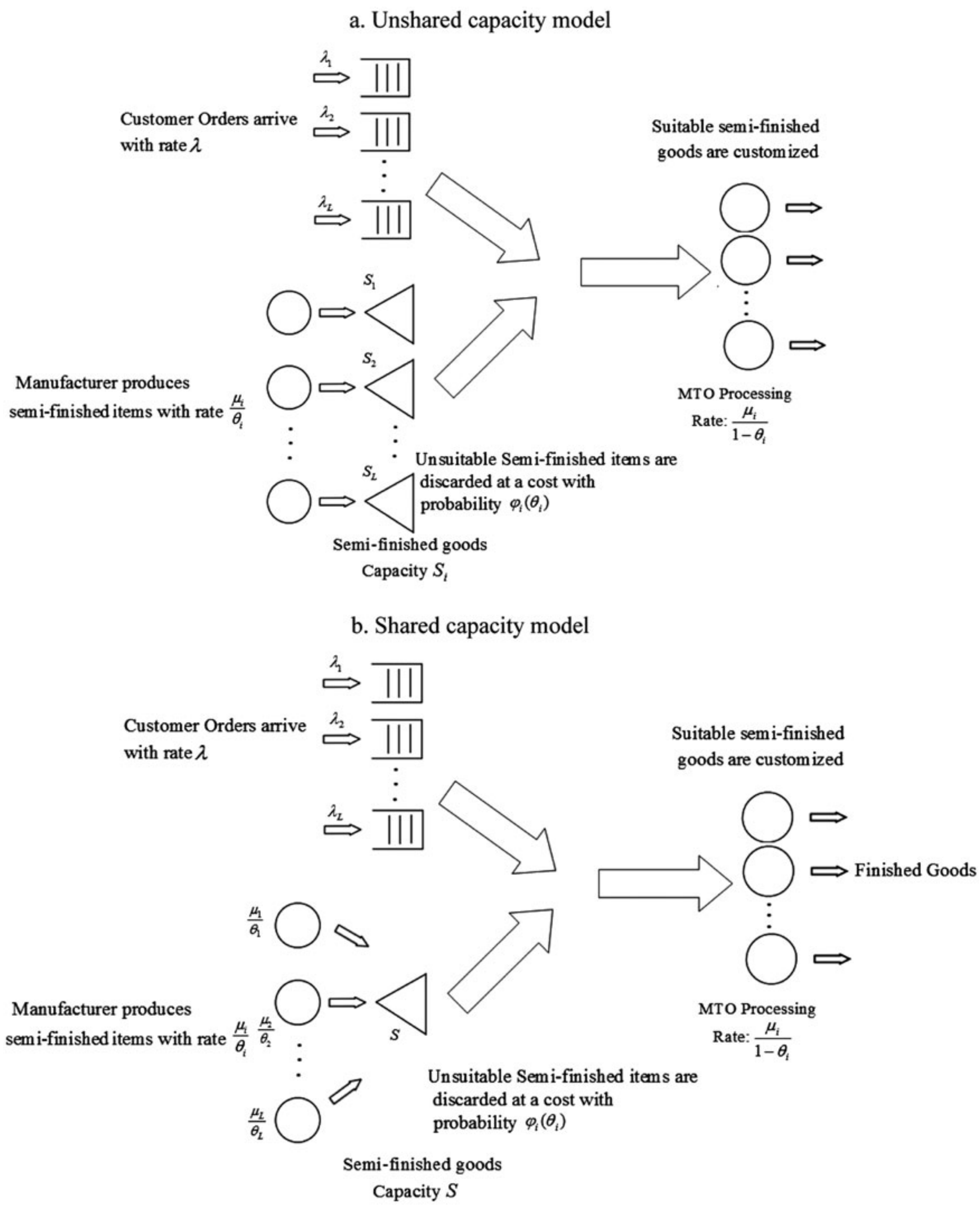

Figure 2. The multi-product hybrid MTS-MTO production supply chain.

studied by Jewkes and Alfa (2009), there is a probability of $\phi_i(\theta_i)$ that a semi-finished product is not suitable for customisation and so $\phi_i(\theta_i)$ is monotonically increasing with θ_i which is a reasonable assumption. The value φ_i can be thought of as a characteristic of the product marketplace. High values of φ_i represent a marketplace for which high degrees of customisability is important to consumers. Low values of φ_i represent a market place in which customisation is less important to customers. In terms of a mathematical representation for φ_i, we may assume, for example, that $\varphi_i = b_i\theta_i^n$, $n \geq 1$; $0 < b_i < 1$. More general forms can be modelled. For the time being, however, we will assume $n = 1$, i.e. $\varphi_i = b_i\theta_i$. A practical value of b_i will depend on characteristics of the customer population. High values of b_i (close to 1.0) means that the market demands a high degree of freedom to specify the final product and is intolerant to deviation. Lower values of b_i might be appropriate if customers will accept a range of product characteristics – i.e. there is a smaller probability that the item will be unsuitable even if it has characteristics stemming from DPD (Jewkes and Alfa 2009).

4. Problem formulation

4.1 *Unshared capacity model*

The entire explained system for unshared capacity model, which is shown in Figure 2(a) in Section 3, can be described by a Markov process with state (n_i, m_i), where n_i is the number of customers in the system waiting for each finished product of type i and m_i is the number of type i semi-finished products in its semi-finished product storage. Therefore, the state space is denoted by $\Omega = \{n_i \geq 0,\ 0 \leq m_i \leq S_i\}$, which is depicted in Figure 3 with transition rates.

In Figure 3, for each product type $a = \frac{\mu(1-\phi)}{\theta}$ and $b = \frac{\mu}{1-\theta}$. The associated balance equations for the steady probabilities follow Equations (3) to (8).

$$\left(\frac{\mu_i(1-\varphi_i)}{\theta_i} + \lambda_i\right) P_i(n_i, m_i) = \frac{\mu_i}{1-\theta_i} P_i(n_i+1, m_i+1), \qquad n_i = 0, m_i = 0 \tag{3}$$

$$\left(\frac{\mu_i(1-\varphi_i)}{\theta_i} + \lambda_i\right) P_i(n_i, m_i) = \frac{\mu_i(1-\varphi_i)}{\theta_i} P_i(n_i, m_i-1) + \frac{\mu_i}{1-\theta_i} P_i(n_i+1, m_i+1), \quad n_i = 0, 1 \leq m_i \leq S_i - 1 \tag{4}$$

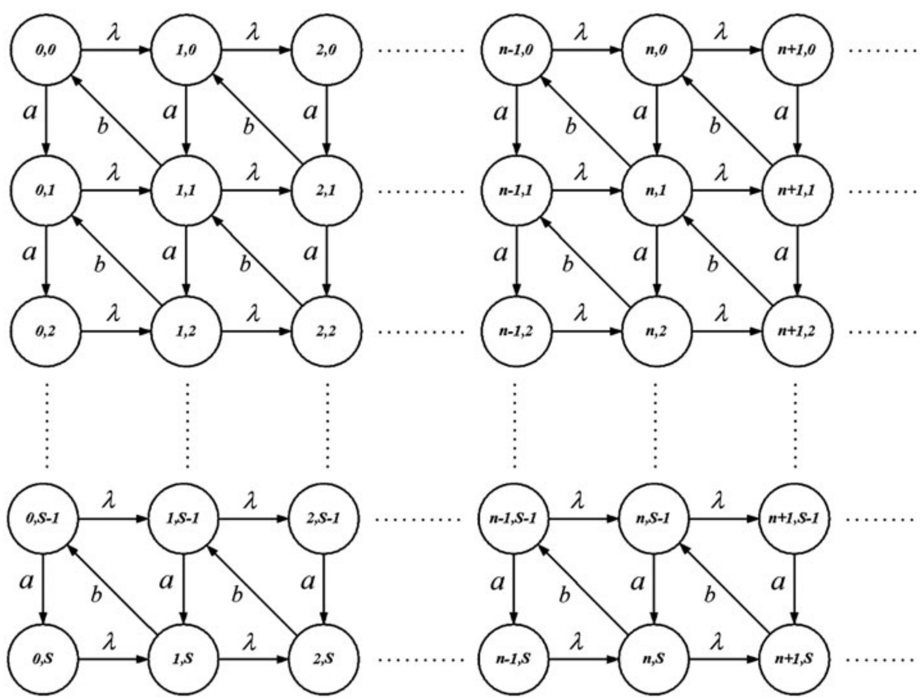

Figure 3. State transition rates diagram.

$$\frac{\mu_i(1-\phi_i)}{\theta_i}P_i(n_i\,,m_i-1)=\lambda_i\,P_i(n_i,m_i),\quad n_i=0\,,m_i=S_i \tag{5}$$

$$\left(\frac{\mu_i(1-\varphi_i)}{\theta_i}+\lambda_i\right)P_i(n_i\,,m_i)=\lambda_i\,P_i(n_i-1\,,m_i)+\frac{\mu_i}{1-\theta_i}P_i(n_i+1\,,m_i+1),\quad 1\leq n_i\,,m_i=0 \tag{6}$$

$$\left(\frac{\mu_i(1-\varphi_i)}{\theta_i}+\lambda_i+\frac{\mu_i}{1-\theta_i}\right)P_i(n_i\,,m_i)=\frac{\mu_i(1-\varphi_i)}{\theta_i}P_i(n_i\,,m_i-1)+\frac{\mu_i}{1-\theta_i}P_i(n_i+1\,,m_i+1)+\lambda_i\,P_i(n_i-1\,,m_i),$$
$$n_i=0,\quad 1\leq m_i\leq S_i-1 \tag{7}$$

$$\left(\lambda_i+\frac{\mu_i}{1-\theta_i}\right)P_i(n_i\,,m_i)=\frac{\mu_i(1-\varphi_i)}{\theta_i}P_i(n_i\,,m_i-1)+\lambda_i\,P_i(n_i-1\,,m_i),\quad 1\leq n_i,\quad m_i=S_i \tag{8}$$

The corresponding generator matrix Q_i written in block form (9) for the product of type i is:

$$Q_i=\begin{bmatrix} D_i & A_i & & & \\ C_i & E_i & A_i & & \\ & C_i & E_i & A_i & \\ & & \ddots & \ddots & \ddots \end{bmatrix} \tag{9}$$

Appendix A shows block matrices where A_i, C_i, E_i and G_i are block matrices with the dimension of $(S_i+1)\times(S_i+1)$. It is notable that A_i giving the rate at which the number of customer orders in the system increases by one, E_i giving the rate at which the number of customer orders in the system either stays at the same level and C_i giving the rate at which the number of customer orders in the system decreases by one. G_i is the matrix rate at which the customer orders in the system move from zero to one.

Let $F_i=A_i+E_i+C_i$ be a generator matrix with its associated stationary distribution $P_i=[P_{i0},P_{i1},...,P_{iS_i}]$ given as a solution to $P_iF_i=0$, $P_i\mathbf{1}=1$.

$$F_i=\begin{bmatrix} F_{i_{0,0}} & F_{i_{0,1}} & & & \\ F_{i_{1,0}} & F_{i_{1,1}} & F_{i_{1,2}} & & \\ & \ddots & \ddots & \ddots & \\ & & F_{i_{S_i-1,S_i-2}} & F_{i_{S_i-1,S_i-1}} & F_{i_{S_i-1,S_i}} \\ & & & F_{i_{S_i,S_i-1}} & F_{i_{S_i,S_i}} \end{bmatrix} \tag{10}$$

Appendix B illustrates block matrices where $F_{i_{m,m+1}}$, $F_{i_{m,m-1}}$, and $F_{i_{m,m}}$ are $(S_i+1)\times(S_i+1)$. As it is discussed in Neuts (1981), the explained Markov chain is stable if $P_iC_i\mathbf{1}>P_iA_i\mathbf{1}$. In order to have a stable system, we require the final production stage to have a service rate that exceeds the arrival rate of customers. In addition, the supply rate of suitable semi-finished products to the final production stage must be more than the customer demands rate.

4.1.1 *Steady state analysis*

The behaviour of this supply chain system is studied in a steady state. Let $\Pi_i=[\Pi_{i\mathbf{0}},\Pi_{i\mathbf{1}},\Pi_{i\mathbf{2}},...]$ be the stationary probabilities associated with the Markov chain for each product type so that $\Pi_iQ_i=0$ and $\Pi_i\mathbf{1}=1$ $(i=1,2)$. Due to the matrix geometric theorem Neuts (1981), equation $\Pi_{i,n+1}=\Pi_{i,n}R_i,\quad n\geq 0$ must be satisfied where R_i is the minimal non-negative solution to the matrix quadratic equation $A_i+R_iE_i+R_i^2C_i=0$.

It is noteworthy that matrix R_i can be computed very easily using some well known methods according to Bolch et al. (1998). A simple way to compute R_i is the iterative approach given as $R_i(n+1)=-(A_i+R_i(n)^2C_i)E_i^{-1}$ until $|R_i(n+1)-R_i(n)|_{nj}<\varepsilon$, with $R_i(0)=0$. The boundary vector Π_{i0} is obtained from $\Pi_{i0}(D_i+R_iC_i)=0$.

4.1.2 *Performance evaluation indices*

Here, the important performance evaluation indices of the system can be obtained as described below. Let $E[O_i]$ be the mean number of customers' orders for product of type i in the system, including the one being served; $E[W_i]$ be the mean customer order completion delay for product of type i; $E[N_i]$ be the mean number of semi-finished products in the system for product of type i, and $E[U_i]$ be the expected number of unsuitable semi-finished products disposed per unit time for product of type i, then

$E[O_i] = \Pi_{i1}(I - R_i)^{-2}\mathbf{1}$
$E[W_i] = \frac{E(O_i)}{\lambda_i}$ (by applying Little's Law),
$E[N_i] = \Pi_{i0}(I - R_i)^{-1}y_i$; where $y_i = [0, 1, 2, ..., S_i]^T$,
$E(U_i) = \dfrac{(1 - \Pr(m_i = S_i))\varphi_i\mu_i}{\theta_i}$; where m_i denotes the number of semi-finished products storage for each product type.

4.1.3 *Mathematical model*

The objective function includes the following costs:

(1) Holding semi-finished products in buffer storage (C_{H_i}).
(2) Establishing semi-finished products storage capacity (C_{C_i}).
(3) Customer order fulfilment delay (C_{W_i}).
(4) Disposing an unsuitable item (C_{u_i}).

The integrated operations-marketing mathematical formulation of the model is as follows:

$$\underset{P_i,S_i,\theta_i}{Max}\ Z(P_i, S_i, \theta_i) = \sum_{i=1}^{L} P_i\lambda_i - \sum_{i=1}^{L} C_{u_i}V(\theta_i)E(U_i) - \sum_{i=1}^{L} C_{h_i}V(\theta_i)E(N_i) - \sum_{i=1}^{L} C_{w_i}E(W_i) - \sum_{i=1}^{L} C_{c_i}S_i \tag{11}$$

St:

$$\frac{(1-\theta_i)}{\mu_i} \geq \tau_i E(W_i) \quad \forall i \tag{12}$$

$$\lambda_i \geq 0 \quad \forall i \tag{13}$$

$$0 < \theta_i < 1.0 \quad \forall i \tag{14}$$

$$S_i = 1, 2, ... \quad \forall i \tag{15}$$

$$P_i \geq 0 \quad \forall i \tag{16}$$

The objective function (11) maximises the total expected profit in the supply chain. The cost structure consists of the cost of semi-finished products that are not consistent with customer's order, expected semi-finished products' holding cost, the cost of establishing storage capacity for semi-finished products, and expected cost of delay in customer order completion which include time of customisation and logistics. According to Jewkes and Alfa (2009), the second production stage wishes to impose a service level constraint to limit the expected customer order fulfilment delay to a set threshold. Empirical studies show that order processing time is typically about 5–20% of order lead time; hence, the second production stage establishes the service level threshold in relation to the average amount of time spent customising a semi-finished item. Therefore, constraint (12) is employed for each product type $\left(\frac{(1-\theta_i)}{\mu_i} \geq \tau_i E(W_i)\right)$. In other words, the mean time it takes for the manufacturer to customise the order, $\frac{\mu_i}{(1-\theta_i)}$, must be at least a fraction τ_i of the overall customer order fulfilment delay. Values of τ are considered in the range of $0.05 \leq \tau_i \leq 0.20$. Constraints (13) and (16) restrict the value of mean arrival rate and price for product of type i to be non-negative. Constraint (14) assures that the percent of completion for product of type i in first production stage is between zero and one. The constraint (15) represents the range of the storage capacity of type i semi-finished products.

The outputs of the represented model are the optimal fractions of the process fulfilled by the manufacturer for each product type, optimal storage capacity of each semi-finished product, and the optimal prices for each product type.

4.1.4 *Solution approach*

Based on the fact proposed in constraint (13) the value of mean arrival rate for product of type i must be non-negative. Considering this constraint, there is an upper bound and a lower bound for each product's price which can be simply determined.

In order to be able to solve Markov-related section of the problem, it is necessary to have the specific amount of λ_i. In this case, it is needed to calculate the amount of λ_i for different values of prices. For the discrete values of prices distributed from the introduced upper bound and lower bound, different values of λ_i are calculated. Then for each λ_i, stochastic values of the objective function Z are calculated with the help of matrix geometric method. The final model will be solved by means of stochastic search in order to specify the optimal values of S_i, θ_i pertaining to the optimal profit function. A numerical example will be proposed in Section 5 to illustrate the function of this solution approach.

4.2 *Shared capacity model*

This section studies a more realistic case that can be considered as a supplement to the proposed model (see Figure 2(b)). According to warehouses physical structure, we cannot establish every calculated optimal storage capacity for each product type. This is a cogent assumption in operational problems. Moreover, specific capacity of S for semi-finished product warehouse is considered. Due to separate calculations of optimal storage capacity for each product type, we cannot apply the storage space constraint in our optimization model. Therefore, if the cumulative semi-finished product storage for all types of products satisfies the warehouse capacity constraint, the obtained solutions can be taken into consideration as optimal storage capacities for products. On the contrary, if the warehouse capacity constraint has not been satisfied, according to Teimoury et al. (2012) we can use the developed heuristic solution procedure as follows.

Algorithm

Step 1: Set $S_0 = (S_1, S_2, \ldots, S_i, \ldots, S_L)$ and $Z_0 = Z(P^*(S_0), S_0, \theta^*(S_0))$.

Step 2: Calculate $\sum S_0$ (cumulative storage value for all product types). If $\sum S_0 \le S$ (S is the predefined capacity constraint for central warehouse), solutions obtained in step 1 are acceptable: stop and set $Z_0 \to Z^*$; $P^*(S_0) \to P^*$; $S_0 \to S^*$; $\theta^*(S_0) \to \theta^*$. Otherwise: Step 3.

Step 3: Set $Z_0 \to Z^{MAX}$; $P^*(S_0) \to P^{MAX}$; $S_0 \to S^{MAX}$; $\theta^*(S_0) \to \theta^{MAX}$.

Step 4: Set $Z^{MAX} = Z\left(P^*\left(S^{MAX}\right), S^{MAX}, \theta^*\left(S^{MAX}\right)\right)$

Step 5: Set $S^{MAX} - 1 \to S^{MAX}$ (if $S^{MAX} - 1$ is stable), $Z_i = Z\left(P^*\left(S^{MAX} - 1\right), S^{MAX} - 1, \theta^*\left(S^{MAX} - 1\right)\right)$ for each product type and solve $\underset{i}{Max}\left(Z_i - Z^{MAX}\right)$.

Step 6: If $\sum S_{i^*} \le S$, solutions obtained in step 3 are acceptable: stop and set $Z_{i^*} \to Z^*$; $P^*(S_{i^*}) \to P^*$; $S_{i^*} \to S^*$; $\theta^*(S_{i^*}) \to \theta^*$. Otherwise: set $Z_{i^*} \to Z^{MAX}$; $P^*(S_{i^*}) \to P^{MAX}$; $S_{i^*} \to S^{MAX}$; $\theta^*(S_{i^*}) \to \theta^{MAX}$ and go to step 3.

The proposed algorithm is represented schematically in Figure 4.

Although the developed algorithm is so time-consuming due to the enumeration technique used in its steps, it computes a nearly optimal solution with minimum benefit loss.

5. Numerical example

We developed the theoretical model in generic terms. In order to apply our model to a real case study, a motor production supply chain network is studied containing two product types with one manufacturer, one retailer, a capacitated warehouse with the capacity of $S = 5$. It is assumed that the demand functions of each product would be as follow.

$$\lambda_1 = 0.2 - 0.05P_1 + 0.01P_2 \ge 0$$

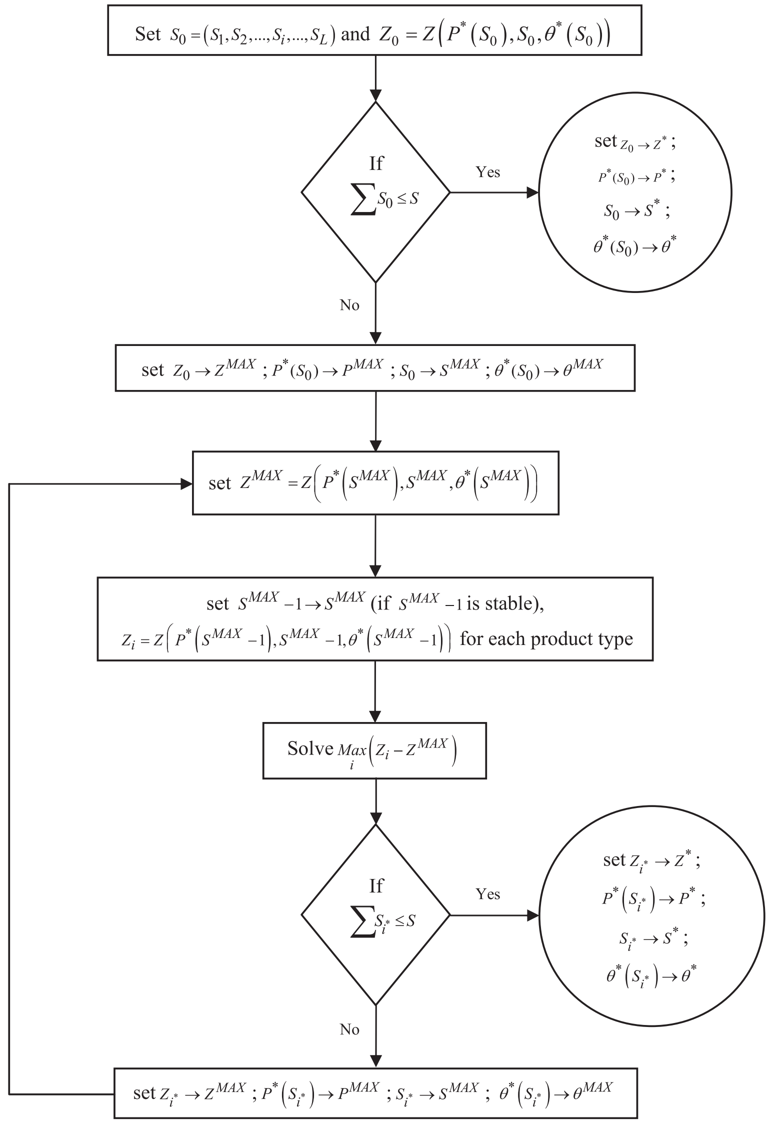

Figure 4. Heuristic solution procedure.

$$\lambda_2 = 0.2 - 0.01P_2 + 0.005P_1 \geq 0$$

Based on the assumed parameters, the feasible solutions of the prices can be calculated easily. Furthermore, each semi-finished product value $V(\theta_i)$ equals to θ_i as assumed by Jewkes and Alfa (2009). Parameters' settings for numerical example, based on the data derived from a real supply chain with two types of motor engines, are:

Table 3. Parameters setting.

	Product *I*	Product *II*
μ_i	0.8	0.7
C_{Ui}	0.0001	0.001
C_{Hi}	0.00001	0.001
C_{Wi}	0.01	0.1
C_{Ci}	0.000005	0.0005
τ_i	0.05	0.05

The integrated operations-marketing mathematical formulation of two product supply chain is as follows:

$$\begin{aligned}\underset{P_1,P_2,S_1,S_2,\theta_1,\theta_2}{Max} \quad Z(P_1,P_2,S_1,S_2,\theta_1,\theta_2) = {} & P_1(\alpha_1-\beta_1P_1+\gamma_1P_2)+P_2(\alpha_2-\beta_2P_2+\gamma_2P_1) \\ & -C_{u1}V(\theta_1)E(U_1)-C_{u2}V(\theta_2)E(U_2)-C_{h1}V(\theta_1)E(N_1) \\ & -C_{h2}V(\theta_2)E(N_2)-C_{w1}E(W_1)-C_{w2}E(W_2)-C_{c1}S_1-C_{c2}S_2\end{aligned}$$

St:

$$\frac{(1-\theta_1)}{\mu_1} \geq \tau_1 E(W_1)$$

$$\frac{(1-\theta_2)}{\mu_2} \geq \tau_2 E(W_2)$$

$$\alpha_1-\beta_1P_1+\gamma_1P_2 \geq 0$$

$$\alpha_2-\beta_2P_2+\gamma_2P_1 \geq 0$$

$$0<\theta_1<1$$

$$0<\theta_2<1$$

$$P_1 \geq 0$$

$$P_2 \geq 0$$

$$S_1 = 1,2,\ldots$$

$$S_2 = 1,2,\ldots$$

The computational results are based on the MATLAB 7.8 implementation where the total cost is computed for $0.01 \leq \theta_i \leq 0.99$ in increments of 0.01 where S_i varies from 1 to 50.

As shown in Table 4, the most beneficial policy is a combination of completing product of type *I* up to 14% based on the predictions and producing the remaining 86% based on the certain demand arrival in the second level, and manufacturing product of type *II* up to 11% based on the predictions and completing 89% based on the certain demand arrival in the second level. In this scenario, a warehouse with capacity of three for product *I* and a warehouse with capacity of two for product *II* are to be established. Moreover, the optimal price for product *I* would be four and for product *II* would be 13. In practice though, these percentages will be adapted to the most conceivable form of product. Furthermore, owing to the low optimal percent of production, it is inevitable that this chain is inclined to produce MTO products. This is conscionably justifiable inasmuch as the cost of disposing an unsuitable item is exorbitant which leads to abrupt reduction in profit function.

The warehouse capacity of ($S = 5$) has to be satisfied in the studied example. Therefore, the satisfaction condition $\sum_{i=1}^{2} S_i^* \leq S$ must be checked and if the storage capacity constraint does not hold, the developed heuristic solution should be implemented:

Table 4. Results of numerical example.

P_1	P_2	θ_1	θ_2	S_1	S_2	$Z\ (P_1, P_2, \theta_1, \theta_2, S_1, S_2)$
1	1	0.10	0.05	1	1	**0.152512171**
1	1	0.10	0.05	1	2	**0.154758246**
1	1	0.10	0.05	1	3	**0.154271065**
1	1	0.10	0.05	1	4	**0.153759719**
1	1	0.10	0.05	1	5	**0.153248809**
…	…	…	…	…	…	...
4	13	0.14	0.11	3	1	**1.512115610**
4	13	0.14	0.11	3	2	**1.514182834**
4	13	0.14	0.11	3	3	**1.513703482**
4	13	0.14	0.11	3	4	**1.513194496**
4	13	0.14	0.11	3	5	**1.512686447**
…	…	…	…	…	…	...
8	24	0.20	0.15	5	1	**0.160320001**
8	24	0.20	0.15	5	2	**0.159817378**
8	24	0.20	0.15	5	3	**0.159316865**
8	24	0.20	0.15	5	4	**0.158816761**
8	24	0.20	0.15	5	5	**0.158316740**

Step 2: $\sum_{i=1}^{2} S_i^* = 3 + 2 = S$

Therefore, the optimal solution can be taken into account as an optimal solution for the shared capacity case either.

Further analysis of profit function is conducted based on the different measures of price, completion percent, and buffer size. Interrelations between these factors are also investigated. Furthermore, the sensitivity analysis of the parameters is performed by comparing the results of two products as follows.

- Variations of profit function for different prices, completion percentages, and buffer sizes

As shown in different parts of Figure 5, increase in price, completion rate, and buffer size, even though it causes an increase in profit, pursues a decrease due to the increase in waiting costs. This leads to the conclusion that there is a maximum value for the percent of completion for the product of type i in first production stage (θ_i), optimal storage capacity of type i semi-finished products (S_i), and price quoted to product of type $i(P_i)$.

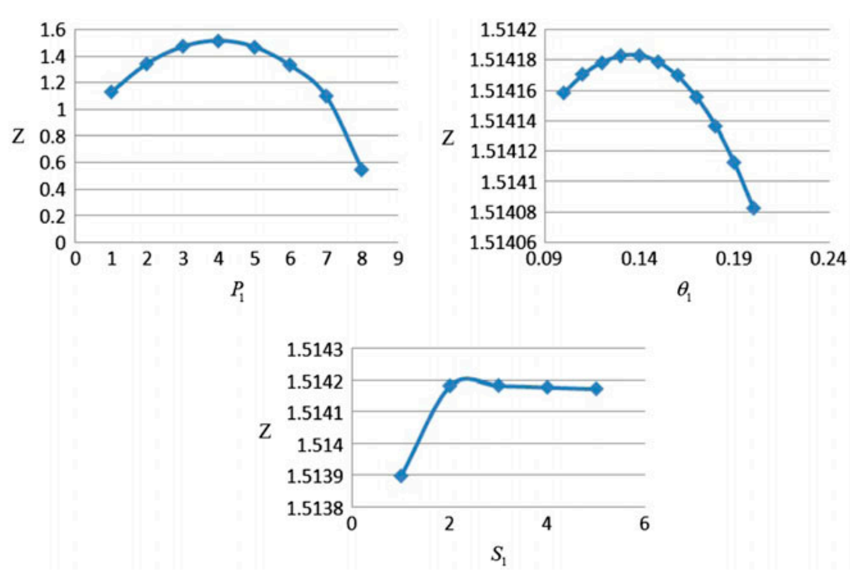

Figure 5. Variations of profit function for different prices, completion percents, and buffer sizes.

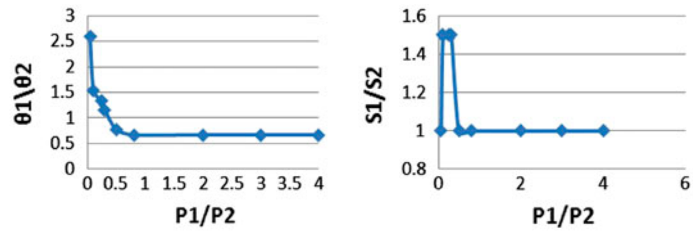

Figure 6. Effect of the variation of the ratio of two products on ratio of completion rates and buffer sizes.

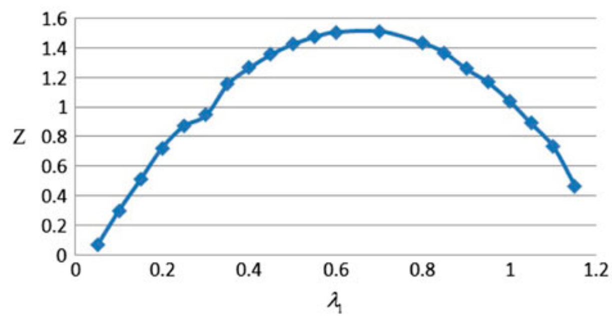

Figure 7. Effect of demand on profit function.

It should be mentioned that only the results of product *I* are disclosed here although the behaviour of product *II* is similar.

- Effect of prices ratio on completion rates ratio and buffer sizes ratio

Figure 6 illustrates how the ratio of the completion rates and buffer size is decreasing in the ratio of prices. Based on these results, whenever the price of product *I* is chosen to be larger than the product *II*, the supply chain is inclined to produce a lower number of product *I* with a lower completion percentage as a result of the variety of customers whom the system serves in virtue of larger demand.

- Effect of demand on profit function

As shown in Figure 7, an increase in average rate of demand, despite an initial increase in profit, follows a decrease due to the augmentation in costs, especially customer waiting costs.

- Sensitivity analysis of the parameters

In Table 5, the cost parameters of each product and the optimal measures for the percent of completion for product of type i in first production stage (θ_i), optimal storage capacity of type i semi-finished products (S_i), and price quoted to product of type $i(P_i)$ are demonstrated.

Table 5. List of cost-related parameters of two products.

		Product *I*				Product *II*
C_{Ui}		0.0001				0.001
C_{Hi}		0.00001				0.001
C_{Wi}		0.01				0.01
C_{Ci}		0.000005				0.0005
$Z\ (P_1, P_2, \theta_1, \theta_2, S_1, S_2)$	P_1	P_2	θ_1	θ_2	S_1	S_2
1.514182834	4	13	0.14	0.11	3	2

Since C_{U_i}, the cost of disposing of an unsuitable item of type *i*, is lower for product *I*, the supply chain is prone to produce product *I* with higher θ. Moreover, the lower cost of C_{W_i}, the cost of customer order fulfilment delay for product of type *i*, for product *I* leads to the same result, since a higher completion percentage reduces the time a customer has to wait for the production of his requested product. On the other hand, higher C_{H_i}, the holding cost for semi-finished products of type *i*, for product *II* in comparison with product *I* is conducive to lower buffer size for product *II*. In addition, lower C_{C_i}, the cost of establishing type *i* semi-finished products storage capacity, for product *I* enhances this effect.

6. Conclusion

For the first time, an integrated operations-marketing queuing-based model for multi-product supply chain is developed to help understand how the OPP affects the trade-off between customer order fulfilment delay and inventory risks, when both stages of production take non-negligible time and when the production capacity is limited. In order to evaluate performance measures, a queuing model and the matrix geometric method were applied. In addition, the problem under shared and unshared capacity is developed. We proposed the theoretical model in generic terms and solved the numerical example for a two products supply chain. Our observations, based on extensive numerical experiments, indicate that adding the price to a manufacturing model helps us not only to investigate the effect of price on manufacturing performance indices, but also to establish marketing strategies to increase the profit.

In this paper, the authors seek to develop a model which simultaneously considers the product pricing decision and OPP positioning under uncertain demand and delivery lead-time with price sensitive demand function. Moreover, there is a practical base; integrating operations-marketing perspective by adding decision on product pricing with assumption of price sensitive demand function and theoretical base; applying a queuing approach for modelling the problem because of uncertain nature of demand arrival and lead-time. Finally, this model helps strategic management of SCM to have integrated operations-marketing perspective. Hence, top managers can have a wider view in their decision makings. Following issues can be considered as future research possibilities:

- Applying the capacity constraint in customers queue: This study investigates the simplest model for the queuing systems. It is more realistic, however, to examine other queuing system models such as M/M/m, M/M/m/k, and so forth.
- Relaxing the assumptions of exponentially distributed arrival and service times: The assumption of exponentially distributed arrival and service time can be relaxed by use of G/G/m models.
- Considering the impatient customers in arrival demands.
- Applying other solution methods: It is possible to use other heuristic and meta-heuristic solution method after carefully scrutinising the dimensions of the mathematical model and its attributes.

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Appendix A

$$D_i = \begin{bmatrix} D_{i_{0,0}} & D_{i_{0,1}} & & & \\ & D_{i_{1,1}} & D_{i_{1,2}} & & \\ & & \ddots & \ddots & \\ & & & D_{i_{S_i-1,S_i-1}} & D_{i_{S_i-1,S_i}} \\ & & & & D_{i_{S_i,S_i}} \end{bmatrix}_{(S_i+1)\times(S_i+1)} \tag{A.1}$$

$$D_{i_{m,m}} = \begin{cases} -(\lambda_i + \frac{\mu_i(1-\phi_i)}{\theta_i}) & 1 \le i \le L, \quad 0 \le m \le S_i - 1 \\ -\lambda_i & 1 \le i \le L, \quad m = S_i \end{cases}$$

$$D_{i_{m,m+1}} = \frac{\mu_i(1-\phi_i)}{\theta_i} \qquad 1 \le i \le L,\ 0 \le m \le S_i - 1$$

$$E_i = \begin{bmatrix} E_{i_{0,0}} & E_{i_{0,1}} & & & \\ & E_{i_{1,1}} & E_{i_{1,2}} & & \\ & & \ddots & \ddots & \\ & & & E_{i_{S_i-1,S_i-1}} & E_{i_{S_i-1,S_i}} \\ & & & & E_{i_{S_i,S_i}} \end{bmatrix}_{(S_i+1)\times(S_i+1)}$$

$$E_{i_{m,m}} = \begin{cases} -\left(\lambda_i + \dfrac{\mu_i(1-\phi_i)}{\theta_i}\right) & 1 \le i \le L,\ m = 0 \\ -\left(\lambda_i + \dfrac{\mu_i(1-\phi_i)}{\theta_i} + \dfrac{\mu_i}{1-\theta_i}\right) & 1 \le i \le L,\ 1 \le m \le S_i - 1 \\ -\left(\lambda_i + \dfrac{\mu_i}{1-\theta_i}\right) & 1 \le i \le L,\ m = S_i \end{cases} \tag{A.2}$$

$$E_{i_{m,m+1}} = \frac{\mu_i(1-\phi_i)}{\theta_i} \qquad 1 \le i \le L,\ 0 \le m \le S_i - 1$$

$$C_i = \begin{bmatrix} 0 & \mathbf{0} \\ I\dfrac{\mu_i}{1-\theta_i} & \mathbf{0} \end{bmatrix}_{(S_i+1)\times(S_i+1)} \tag{A.3}$$

$$A_i = [I\lambda_i]_{(S_i+1)\times(S_i+1)} \tag{A.4}$$

Appendix B

$$F_{i_{m,m}} = \begin{cases} -\left(\dfrac{\mu_i(1-\phi_i)}{\theta_i}\right) & 1 \le i \le L,\ m = 0 \\ -\left(\dfrac{\mu_i(1-\phi_i)}{\theta_i} + \dfrac{\mu_i}{1-\theta_i}\right) & 1 \le i \le L,\ 1 \le m \le S_i - 1 \\ -\left(\dfrac{\mu_i}{1-\theta_i}\right) & 1 \le i \le L,\ m = S_i \end{cases} \tag{B.1}$$

$$F_{i_{m,m+1}} = \frac{\mu_i(1-\phi_i)}{\theta_i} \qquad 1 \le i \le L,\ 0 \le m \le S_i - 1 \tag{B.2}$$

$$F_{i_{m,m-1}} = \frac{\mu_i}{1-\theta_i} \qquad 1 \le i \le L,\ 1 \le m \le S_i \tag{B.3}$$