A Queueing-Game Model for Making Decisions About Order Penetration Point in Supply Chain in Competitive Environment

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ABSTRACT

This study is dedicated to Order Penetration Point (OPP) strategic decision making which is the boundary between Make-To-Order (MTO) and Make-To-Stock (MTS) policies. This paper considers two competing supply chains in which a manufacturer produces semi-finished items on a MTS basis for a retailer that will customize the items on a MTO basis. The two-echelon supply chain offers multi-product 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. Moreover, the authors consider both integrated scenario (shared capacity model) and competition scenario (Stackelberg queueing-game model) in this paper. A matrix geometric method is utilized to evaluate various performance measures for this system and then, optimal solutions are obtained by enumeration techniques. The suggested queueing approach is based on a new perspective between the operation and marketing functions which captures the interactions between several factors including inventory level, price, 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 in both scenarios.

Keywords: *Competitive Environment, Game Theory, Integrated Operations-Marketing Perspective, Make-To-Order (MTO), Make-To-Stock (MTS), Matrix Geometric Method (MGM), MTS-MTO Queue, Order Penetration Point (OPP), Queueing System, Supply Chain*

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1. INTRODUCTION

One production system which has recently attracted researchers' and practitioners' consideration is hybrid MTS-MTO (Rafiei & 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, the MTO producers can provide a variety of products and custom orders with lower inventory risks, although they usually have longer customer lead times. Moreover, in MTS production, products are stocked in advance, while in MTO production, a product only starts to be produced when an order of demand is received. The MTS-MTO supply chain is appropriate where common modules are shared by various finished products through divergent finalization. The MTS-MTO supply chain inherits two key characteristics. First, it can lower the cost by taking advantage of economies of scale during the MTS stage for the production of standard modules. Second, it can concurrently satisfy the requirement of high product variety by taking advantage of the MTO stage's flexibility (Wang et al., 2011). The Order Penetration Point (OPP) specifies where the customer's desired specifications influence the production value chain (Hoekstra et al., 1992) and the customer's specifications are considered in different places along the production systems in MTS, MTO and MTS-MTO.

The positioning of OPP is a challenging area that has received increasing attention in the manufacturing strategy literature (Hallgren & Olhager, 2006). According to Teimoury and Fathi (2013), 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), Teimoury and Fathi (2013), Teimoury et al. (2013), current research) are in MTS, MTO, and MTS-MTO environment, respectively.

The motivation for this study is that companies are showing increasing interest in incorporating the OPP as an important input into the strategic design of supply chains in competitive environment. Moreover, making decision on the price of products in competitive supply chains with price sensitive demand function is considered as a strategic decision-making with respect to location of the OPP. In practical competitive 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 competitive 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 in competitive environment. The rest of the paper is organized 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 integrated scenario (shared capacity model) in Section 4.1 and competition scenario (Stackelberg queueing-game model) scenarios in Section 4.2. Besides, the queueing 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

2.1. Order Penetration Point

There are a number of papers addressing the issue of making decisions on OPP which appeared in the literature with various names such as Decoupling Point (DP), Delayed Product Differentiation (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 et al., 2004; Akkerman et al., 2004), steel mills Kerkkanen (2007), semiconductor plants Chang et al. (2003), timber industry Yáñez et al. (2009) and personal computer manufacturing firms Vidyarthi et al. (2009). There is also a large amount of literature explicitly dealing with the hybrid MTO–MTS problem (Sox et al., 1997; Carr & Duenyas, 2000; Soman et al., 2004; Hallgren & Olhager, 2006; Perona et al., 2009; Jewkes & Alfa, 2009;Teimoury et al., 2012; Teimoury & Fathi, 2012). A comprehensive literature review on MTS-MTO production systems and revenue management of demand fulfillment can be found in Perona et al. (2009) and Quante et al. (2009).

Adan and Van der Wal (1998) studied the effect of MTS and MTO production policies on order satisfaction lead-times. Arreola-Risa & DeCroix (1998) analyzed 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) http://www.springerlink.com/content/?Author =Yavuz+G%c3%bcnalaystudied 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 minimize 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) analyzed 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 queueing 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) added 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 analyzed the optimal point of postponement in a multi-stage queueing 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 realize how the degree of DPD affects the tradeoff between customer order completion postponement and inventory risks, when both stages of production have non-negligible time and the production capacity is limited. However, their model did not consider the demand to be a function of price. Teimoury and Fathi (2013a) 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. This help to view the problem in an integrated operation-marketing perspective which has become more practical to manager.

Recently, Ahmadi and Teimouri (2008) studied the problem of where to locate the OPP in an Auto Exportsupply chain by using dynamic programming. Teimoury et al. (2010) proposed an integrated two stage inventory-queue model and production planning model based on queueing approach in real case study of PAKSHOO chemicals company uncertain demands. Teimoury and Fathi (2013b) developed a queuing model for locating OPP in a two-echelon supply chain with impatient customers. Teimoury et al. (2012) proposed a queueing model for making decisions about OPP in multi-echelon supply chains. However, they did not consider in an integrated framework of operation-marketing. Furthermore, a notable literature review in positioning DPs and studying the positioning of multiple DPs in a supply network can be seen in Sun et al. (2008); however, their positioning model did not make any decisions about the optimal semi-finished buffer size and optimal fraction of processing time fulfilled by the upstream of DP. Wong et al. (2009) studied postponement based on the positioning of the differentiation points and the stocking policy. 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 queueing approach for making decisions about OPP in competitive supply chains. 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 Wong and Eyers (2011), O'Leary-Kelly and Flores (2002), Ho and Zheng (2004), Oliva and Watson (2011), Ray (2005), Rao (2009), Erickson (2011), Feng et al. (2008), Vandaele and Perdu (2010), Ioannidis and Kouikoglou (2008), Feng et al. (2010) and Chayet et al. (2004). Many applications and methods for determining the OPP are also presented in Olhager (2003, 2010), Yang and Burns (2003), Yang et al. (2004), Rudberg and Wikner (2004), Wikner and Rudberg (2005), Skipworth and Harrison (2004, 2006), Harrison and Skipworth (2008), Wong et al. (2009), Banerjee et al. (2011), Mikkola and Skjøtt-Larsen (2004) and Choi et al. (2012). Moreover, following authors have developed their models based on queueing approach (Arreola-Risa & DeCroix, 1998; Gupta & Benjaafar, 2004; Wong et al., 2009; Jewkes & Alfa, 2009; Wee & Dada, 2010; Su et al., 2010; Wong et al., 2010; Wong & Eyers, 2011; Teimoury et al., 2010; Teimoury et al., 2011; Teimoury et al., 2012; Teimoury & Fathi, 2013; Teimoury & Fathi, 2013; Teimoury et al., 2013).

2.2. Game Theory Models in Competitive Supply Chains

Competition between supply chains to achieve greater market share in competitive environment is a common theme in literature. Several strategies have been discussed to integrate the business process and activities of internal elements in a supply chain to improve system-wide performance of the chain in terms of price, delivery time and customer service. Using the Internet and applying electronic processes is one of those strategies to bring a core competency. Mendelson and Whang (1990) proposed an $M / M / 1$ queuing model with multiple user classes that price plays dual role: determination of priorities and allocation of service capacity. They presented an incentive-compatible pricing mechanism in the sense that both the execution priorities and arrival rates maximize the expected net value of the system which is determined on a decentralized basis. Dewan and Mendelson (1990) investigated optimal allocation decisions for a service facility, taking into account both the capacity cost and users' delay cost, and modeled the facility as a queuing system in which users have general nonlinear delay cost functions assuming that service requests are homogeneous. Stidham (1992) studied a service facility with a restriction in the arrival rate in the long-run pricing and capacity design problem. Lee and Kim (1993) formulated two models for a single product with stable demand to determine price, demand, lot size and marketing expenditure: the full integration model which determines all decisions involved simultaneously, and the partial integration model that separates the lot sizing decision from the others. Li and Lee (1994) studied Pricing and delivery-time performance in a competitive environment. Lederer and Li (1997) used a competitive model to find the effect of responsiveness on prices, supply chain's profits and customer demands in two cases: in the first case supply chains are different in mean processing time, processing time variety and cost where customers are homogeneous. In the second case supply chains are different in mean processing time and cost

Table 1. Details of our developed OPP models

Authors	Problem	Supply Chain Environment	Demand	Customer Type	OPP	Modeling Method	Research Questions
Teimoury et al. (2011)	A queueing approach to production-inventory planning for supply chain with uncertain demands: Case study of PAKSHOO Chemicals Company	MTS	Poissonprocess	Multi classes	Located at the end of supply chain network	Stochastic modeling and optimization, Queueing and Markov chain modeling	• How can the operational decisions of production-inventory planning be optimized simultaneously in the MTS supply chain environment? • Can queueing 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 queueing 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 queueing approach can be applied to optimize price, delivery lead-time and capacity?
Teimoury et al. (2012)	A queuing approach for making decisions about order penetration point in multiechelon supply chains	MTS-MTO	Poissonprocess	Multi classes	Decision variable		• Can queueing approach be applied to determine the OPP of a multi-product supply chain in MTS-MTO environment? • How stochastic modeling and optimization 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 optimized?
Teimoury & Fathi (2012)	A queueing approach for making decisions about order penetration point in supply chain with impatient customer	MTS-MTO	Poissonprocess	Single class, impatient customer	Decision variable		• Can queueing approach be applied to determine the OPP of a supply chain with impatient customers in MTS-MTO environment? • How stochastic modeling 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?
Teimoury & Fathi (2013)	An integrated operations-marketing perspective for making decisions about order penetration point in multi-product supply chain: A queueing approach	MTS-MTO	price sensitive demand function	Multi classes	Decision variable		• Can queueing 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 modeling and optimization 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?
Teimoury et al. (2013)	An integrated queueing optimization model for making decisions about order penetration point and common platform in supply chain	MTS-MTO	Poisson process	Multi classes	Decision variable		• What is the best balancing between product variety and the configuration of production line and suppliers? • Where is the best choice for OPP? • What combination of the product price and the product features can satisfy customers and provide acceptable financial result for the investors?

continued on following page

Table 1. Continued

Authors	Problem	Supply Chain Environment	Demand	Customer Type	OPP	Modeling Method	Research Questions
Current research	A queueing-game model for making decisions about order penetration point in supply chain in competitive environment	MTS-MTO	price sensitive demand function	Single class	Decision variable	Game theory	• Can game theory be applied to determine the OPP of competitive supply chains with an integrated operations-marketing perspective in MTS-MTO environment? • How stochastic modeling and optimization 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?

where customers are differentiated by demand function and delay sensitivity. Palaka et al. (1998) developed a model for delay-sensitive customers, and the firm which pays lateness penalties whenever the actual lead-time exceeds the quoted lead-time. They also investigated the implications of considering the firm's congestion costs as well as users' delay costs for the capacity utilization, optimal lead-time setting, and pricing decisions of a profit maximizing firm. So and Song (1998) developed an optimization model to determine the joint optimal selection of pricing, delivery time guarantee and capacity expansion and studied the interrelations between them. Tsay and Agrawal (2000) proposed the case of two competing retailers who receive a product from same supplier, and then sell products to an external market. Their research provided understanding about the behavioral signatures of decentralized distribution channels. So (2000) developed a decision model to examine the effects of using quoted delivery time on competition. They assumed that demands are sensitive to price and delivery time and objective function was maximizing the operation profit. They developed a model for each supply chain separately and then expanded each of the models to encompass the conditions in competitive environment. Boyaci and Ray (2003) studied a supply chain with two products different in prices and delivery times. They developed an integrated model to generate some scenarios to decide about constrained capacity for none, one, or both products. Ray and Jewkes (2004) focused on customer lead time management when both demand and price are lead time-sensitive. Afeche and Mendelson (2004) designed a model to select alternative price-service for a supply chain serving in a monopolistic market. They added penalty cost structure for delays relevant to type of service. Dai et al. (2005) introduced the pricing strategies of multiple competitive firms which provide the same service for a common pool of customers where demand at each firm is a linear function. Leng and Parlar (2005) provided an excellent review on game theoretical applications in supply chain management. Pekgun et al. (2006) analyzed two supply chains competing based on price and delivery time in a common market with common services. They examined the impact of centralization of decisions comparing some scenarios in which none, one or both of supply chains are decentralized. Allon and Federgruen (2007) studied a market for an industry of competing service facilities. They modeled each of the service facilities as a single-server $\mathrm{M}/\mathrm{M}/1$ queuing facility, which receives a given company-specific price for each customer served. Boyaci and Ray (2006) developed a model to consider the effect of capacity costs to form the optimal differentiation strategy in terms of prices, delivery times, and delivery reliabilities to maximize the profit of firm which sells two products in a capacitated market. (Liu, Parlar et al. 2007) constructed a Stackelberg game to analyze the price and lead time decisions when a supplier acts as leader and determines the lead-time and a retailer acts as follower and determines the price in a decentralized supply chain. Dobson and Stavrulaki (2007) analyzed a single-facility problem to find out how a monopolist firm, who sells a single product to time-sensitive customers, would set the capacity, locate its facilities and determine the price of the product offered to maximize profits. Pangburn and Stavrulaki (2008) analyzed price and capacity levels to maximize profit of a chain in a monopolist market and found that a hybrid strategy based on a prioritized queuing discipline which combines elements of segmentation and pooling, can outperform both the pure segmentation and pooling strategies. Zhao (2008) assumed that retailers face stochastic demand competition on both price and inventory and focused on how a supplier should set contract in a supply chain system with these retailers. Pekgun et al. (2008) examined a supply chain that serves price- and time-sensitive customers. In their model, decisions of price and delivery time were made by marketing and production department, respectively. Fathian et al. (2009) presented an algorithm to determine an optimal price in internet based service providers for non-digital products that are sold via web sites. Ata and Van Mieghem (2009) studied the effect of dynamic resource substitution in service systems on capacity requirements and responsiveness. They investigated whether two separate markets should be served by separate resources or by an integrated network where two markets dynamically share their resource. Anderson and Bao (2010) investigated price competition with a linear demand function and compared two scenarios: In the first scenario, the supply chain is centralized and each distribution channel is vertically integrated, while in the second scenario, each element acts independently. Sinhaet al. (2010) modeled a priority queuing system for the optimal use of excess capacity of a resource which is shared by two classes of customers consisted of primary (existing) customers and secondary (new) customers. Jayaswalet al. (2011) analyzed a supply chain in a market with two kinds of customers. In their work, the firm serves two different products with different prices and delivery times. They could choose dedicated or shared capacity in operational level and substituted products to achieve larger share of the market. Their aim was finding the best strategy for each production capacity and price to maximize whole profit of the chain. Xiao and Qi (2012) studied the equilibrium decisions in a two-stage supply chain with an all-unit quantity discount contract where the downstream manufacturer's demand is sensitive to three factors: the announced delivery lead-time, the delivery reliability and the selling price of the product. They considered four different scenarios and found that an all-unit quantity discount scheme is preferable for the supply chain in most cases. Teimoury et al. (2011) investigated price, delivery time, and capacity decisions in an $M/M/1$ make-to-order/service system with segmented market. Also, many applications and methods for selecting best strategy of pricing and delivery time decision making are surveyed in Sinha andSarmah (2010), Huaet al. (2010).

The mathematical models in OPP literature commonly seek a balance between inventory costs and customer service levels. However, competitive OPP positioning has not been noticed in literature to the authors' knowledge. The novel proposed queueing-game approach is based on a new perspective between the operation and marketing functions which captures the interactions between several factors including inventory level, price, OPP, and delivery lead time. Moreover, the proposed model seeks to maximize the revenue of the competitive supply chains. Therefore, the model should optimize the price of product and this make an integrated operations-marketing interface perspective which has become more practical and more comprehendible to competitive supply chain managers. The goal of this paper is to find equilibrium customer service levels with inventory costs, such as developed models as in Teimoury and Fathi (2013), Teimoury et al. (2012) and Jewkes and Alfa (2009) in the literature. However, ours differs from the studied articles in several ways. First, OPP positioning model based on queueing-game approach for the first time is proposed in competitive supply chains. Second, the developed model is considered for two competitive supply chains. Third, demand function is considered to be a function of prices of competitive products which are replaceable. The model optimizes both marketing and operation simultaneously.

The competitive 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 customize the products based on an MTO policy. The semi-finished products will be completed as a result of specific customer orders. The developed queueing-game model obtains the optimal prices of competitive products for the completed products to each demand point. In order to balance the costs of customer order fulfillment delay and inventory costs of competitive products, competitive retailers try to find the optimal fraction of processing performed by the competitive manufacturers and its optimal semi-finished competitive products buffer storage.

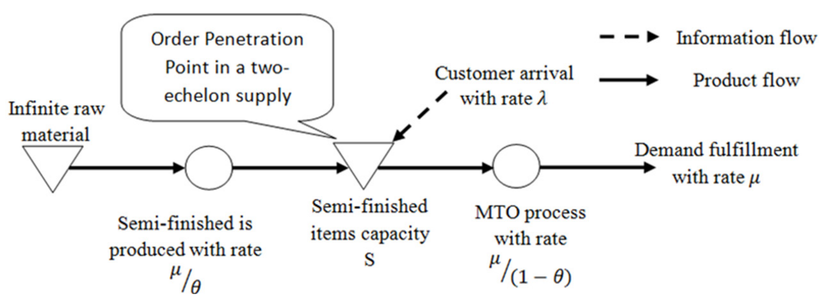
3. PROBLEM DESCRIPTION AND LIST OF NOTATION

The following notations are used for the mathematical formulation of considered model.

- Sets and indices:
  - Supply chain index $i = 1,2$ i
  - Semi-finished products buffer storage capacity for product of supply chain i index $m_i = 1, 2, \ldots, S_i$ m_i
- *Decision variables:*
  - Percent of completion for product of chain i in first production stage θ_i
  - Storage capacity of supply chain i semi-finished products S_i
  - Price quoted to product of supply chain i P_i
- *Parameters:*
  - The value per unit of semi-finished products (dollar/unit) $V(\theta_i)$
  - Constant fraction of the MTO processing rate for product of supply chain i τ_i
  - Mean production rate for product of supply chain i μ_i
  - The holding cost for semi-finished products of supply chain i (dollar/unit) C_{Hi}
  - The cost of customer order fulfillment delay for product of supply chain i (dollar/unit) C_{Wi}
  - The cost of establishing supply chain i semi-finished products storage capacity (dollar/unit) C_{Ci}
  - The cost of disposing an unsuitable item of supply chain i (dollar/unit) C_{ui}
  - Mean arrival rate for product of supply chain i λ_i
- *Expected performance measures:*
  - The expected number of supply chain i semi-finished products in the system $E(N_i)$
  - The expected customer order completion delay for product of supply chain i– the time from when a customer order enters the system until its product is completed $E(W_i)$
  - The expected number of supply chain i unsuitable products produced per unit time $E(U_i)$

Two competitive production supply chains are 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 customizing the semi-finished goods to customer specifications. It is assumed that the studied supply chains offer two competitive products to a market comprising homogenous customers that differ in their preferences for willingness to pay. It is considered that competitive retailers are dealing

Figure 1. The hybrid MTS-MTO production supply chain



with single type of customers who have different Poisson demand rate and are sensitive to price of the requested product and other competitive product. The demands are differentiated based on the products. According to Tsay and Agrawal (2000), Boyaci and Ray (2007) and Teimoury et al. (2011), for two products competitive supply chains, the competitive demand rates are modeled using the linear functions as follow:

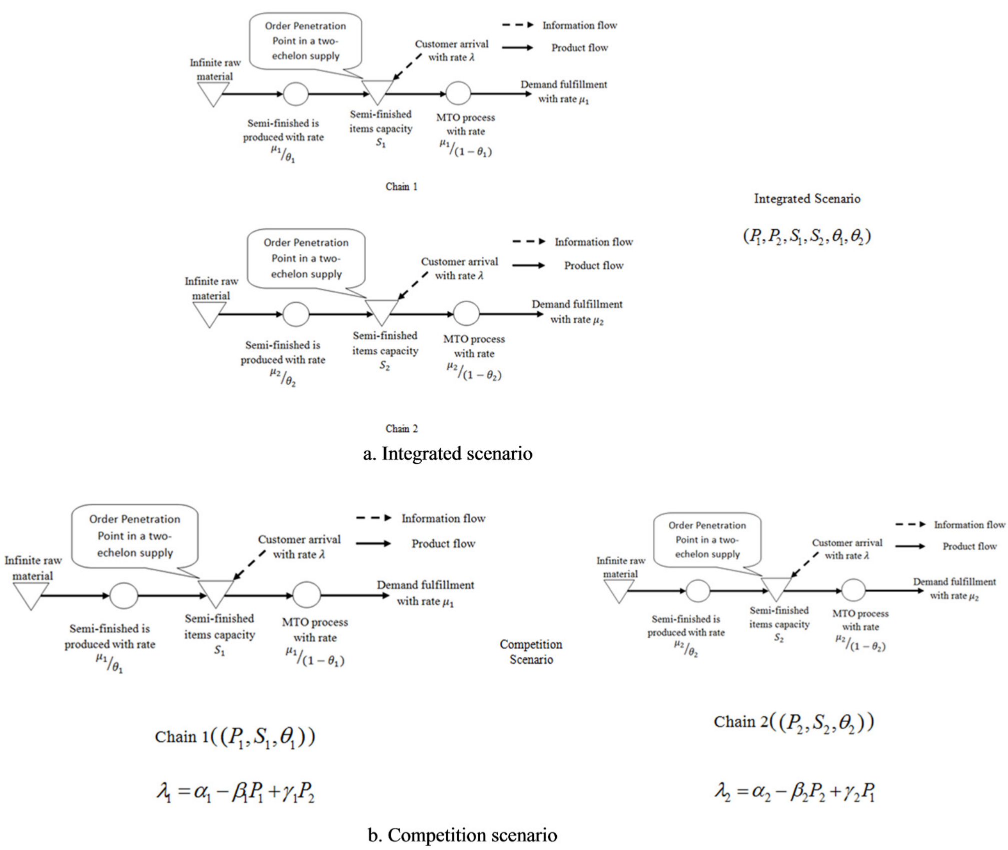
$$\lambda_1 = \alpha_1 - \beta_1 P_1 + \gamma_1 P_2 \quad (1)$$

$$\lambda_2 = \alpha_2 - \beta_2 P_2 + \gamma_2 P_1 \quad (2)$$

The proposed model seeks to maximize the revenue of the competitive supply chains. Therefore, the model should optimize the price of each competitive product type and this make an integrated operations-marketing interface perspective. In this system, customers arrive at random times and each customer requests one unit of product. The times between successive customer arrivals for competitive supply chains are independent random variables with rate λ_i in accordance to a Poisson process. The production times of workstations for competitive product types are assumed to be exponentially distributed with rates $\mu_i,\ i = 1,2$. Moreover, it is supposed that the competitive manufacture has an infinite source of raw materials and never faces shortage. The second competitive production stage has to determine the optimal storage capacity of competitive semi-finished products in supply chain i ($S_i,\ i = 1,2$). Figure 2a and Figure 2b illustrate a diagram depicting the model under both integrated scenario (shared capacity model) (Section 4.1) and competition scenario (Stackelberg queueing-game model) (Section 4.2), respectively. It is assumed that market is sensitive to price and delivery time of both chains.

As shown in Figure 2, the competitive manufacturer provides undifferentiated semi-finished products to the final production stage. For supply chain *i*, 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 organization from the retailer; the ‘‘manufacturer’’ and ‘‘final production stage’’ may be two successive stages in a same organization. We modeled θ_i in supply chain *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 in supply chain *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 studied by Jewkes and Alfa (2009), there is a probability of $\varphi_i(\theta_i)$ in supply chain *i* that a semi-finished product is not suitable for customization and so $\varphi_i(\theta_i)$ 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 the ability to customize to a high degree is important to consumers. Low values of φ_i represent a market place in which customization 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 modeled, however, for the time being, we will assume $n = 1$, i.e., $\varphi_i = b_i\theta_i$. A practical value of b_i in supply chain *i* will depend on characteristics of the customer population. High values (close to 1.0) of b_i means that the market demands a high degree of ability specify the final product and is intolerant to deviation. Lower values of b_i might be

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



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 & Alfa, 2009).

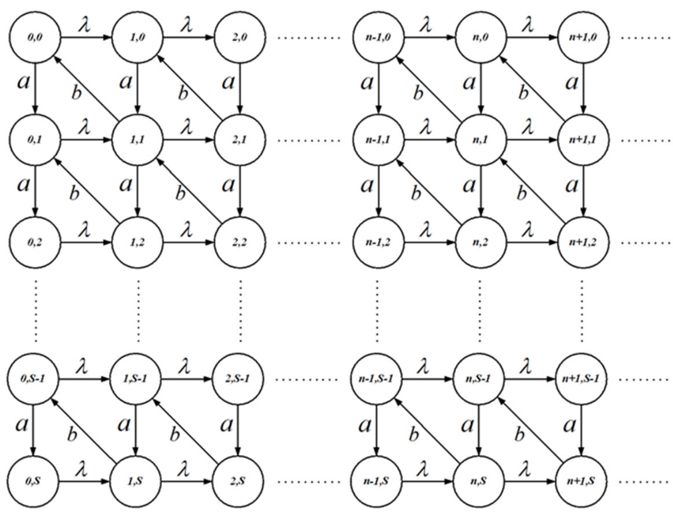
4. PROBLEM FORMULATION

The entire explained system for supply chain *i* model as shown in Figure 2b 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 finished product in supply chain *i* and m_i is the number of supply chain *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 competitive product type $a = \dfrac{\mu(1-\varphi)}{\theta}$ and $b = \dfrac{\mu}{1-\theta}$. The associated balance equations for the steady probabilities follow equations (3) to (8).

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

Figure 3. State transition rates diagram (Teimoury et al., 2012)



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

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

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

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

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

The corresponding generator matrix Q_i written in block form (9) for the product in supply chain *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 $P_i F_i = 0, P_i \mathbf{1} = 1$.

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

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 $P_i C_i \mathbf{1} > P_i A_i \mathbf{1}$. 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. Steady State Analysis

The behavior 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 supply chain i so that $\Pi_i Q_i = 0$ 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 $A_i + R_i E_i + R_i^2 C_i = 0$.

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

4.2. Performance Evaluation Indexes

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

$$E[O_i] = \Pi_{i1}(I - R_i)^{-2}\mathbf{1}$$

$$E[W_i] = {E(O_i)} \big/ {\lambda_i}$$

(By applying Little's Law),

$$E[N_i] = \Pi_{i0}(I - R_i)^{-1} y_i;$$

Where

$$y_i = [0,1,2,...,S_i]^T,$$

$$E(U_i) = \frac{(1 - \Pr(m_i = S_i))\varphi_i \mu_i}{\theta_i};$$

Where m_i denotes the number of semi-finished products storage for supply chain *i*.

4.2.1. Mathematical Model

The objective function includes the following costs:

1. Holding semi-finished products in buffer storage in supply chain *i* (C_{Hi}).
2. Establishing semi-finished products storage capacity in supply chain *i* (C_{Ci}).
3. Customer order fulfillment delay in supply chain *i* (C_{Wi}).
4. Disposing an unsuitable item in supply chain *i* (C_{ui})

4.3. Scenario 1- Stackelberg Game

In this section, the Stackelberg queueing-game model is developed for competition scenario. At first, there is a chain in a monopoly market where acts traditionally, then second chain comes to the market and the market changes to duopoly and two chains start to compete with each other to obtain more market share. Competition continues until equilibrium in to the market and all state be stabled.

The operations-marketing mathematical formulation of the model for supply chain *i* is as follows:

$$\underset{P_i,S_i,\theta_i}{Max}\ Z(P_i,S_i,\theta_i) = P_i\lambda - C_{u_i} V(\theta_i)E(U_i) - C_{h_i} V(\theta_i)E(N_i) - C_{w_i} E(W_i) - C_{c_i} S_i \tag{11}$$

St:

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

$$\lambda_i \geq 0 \tag{13}$$

$$0 < \theta_i < 1.0 \tag{14}$$

$$S_i = 1, 2, \ldots \tag{15}$$

$$P_i \geq 0 \tag{16}$$

The objective function (11) maximizes 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 customization 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 fulfillment 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 customizing a semi-finished item. Therefore, constraint (12) is employed for supply chain *i* ($\frac{(1-\theta_i)}{\mu_i} \geq \tau_i E(W_i)$). In other words, the mean time it takes for the manufacturer to customize the order, $\frac{\mu_i}{(1-\theta_i)}$, must be at least a fraction τ_i of the overall customer order fulfillment delay. Values of τ are considered in the range $0.05 \leq \tau_i \leq 0.20$. Constraint (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 supply chain *i*, optimal storage capacity of each semi-finished product, and the optimal prices for supply chain *i*. The solution approach is the same as presented in Teimoury and Fathi (2013). The proposed game-queueing model is represented schematically in Figure 4.

We can use the developed Stackelberg Game procedure as follows:

Step 0: set $P_2^* = 0$.

Step 1: Chain 1 determines (S_1, θ_1) with the assumption of $P_2 = P_2^*$ and announces $(P_1^*, S_1^*, \theta_1^*)$ to chain 2.

Step 2: Chain 2 makes its decision due to chain 1's $(P_1^*, S_1^*, \theta_1^*)$ and announces $(P_2^*, S_2^*, \theta_2^*)$ to chain 1.

Step 3: If $\left|(P_2^*, S_2^*, \theta_2^*) - (P_1^*, S_1^*, \theta_1^*)\right| < \varepsilon$: stop and . Otherwise: go to step 1.

4.4. Scenario 2- Integrated

In this section, integrated scenario is studied. The integrated operations-marketing mathematical formulation of the model is as follows:

Figure 4. Stackelberg game procedure

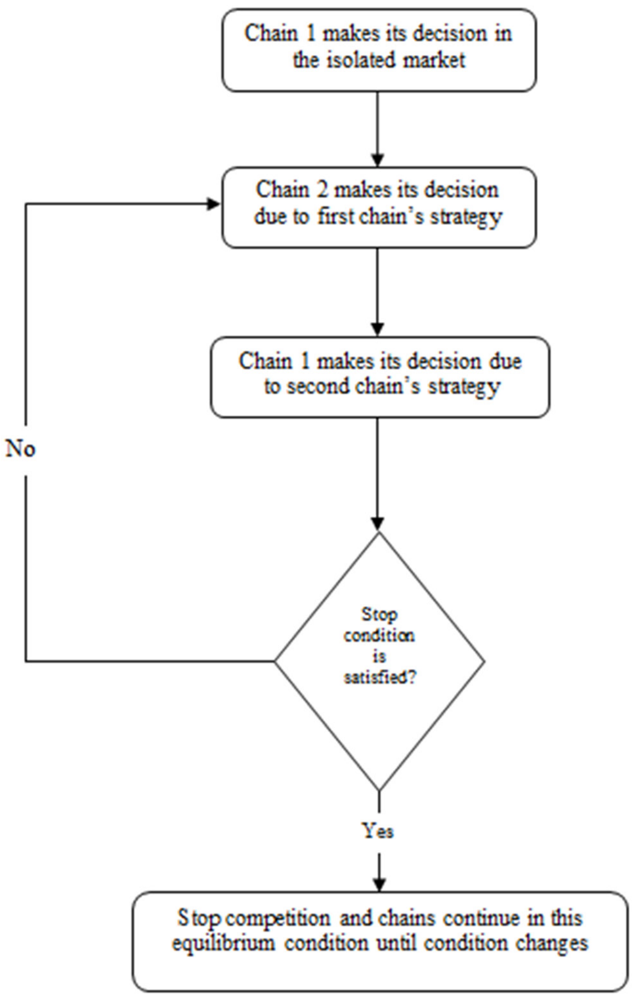


Table 2. Parameters setting

	Chain 1	Chain 2
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

$$\underset{P_i,S_i,\theta_i}{Max}\ Z(P_i,S_i,\theta_i) = \sum_{i=1}^{2} P_i\lambda_i - \sum_{i=1}^{2} C_{u_i} V(\theta_i) E(U_i) - \sum_{i=1}^{2} C_{h_i} V(\theta_i) E(N_i) - \sum_{i=1}^{2} C_{w_i} E(W_i) - \sum_{i=1}^{2} C_{c_i} S_i \tag{17}$$

St:

$$\frac{(1-\theta_i)}{\mu_i} \geq \tau_i E(W_i) \quad \forall i \tag{18}$$

$$\lambda_i \geq 0 \quad \forall i \tag{19}$$

$$0 < \theta_i < 1.0 \quad \forall i \tag{20}$$

$$S_i = 1,2,\ldots \quad \forall i \tag{21}$$

$$P_i \geq 0 \quad \forall i \tag{22}$$

According to Teimoury and Fathi (2013) we can use the developed heuristic solution procedure for solving the mathematical problem.

5. NUMERICAL EXAMPLE

In this section two competing supply chains is considered under integrated scenario. The competing supply chain networks are studied containing two product types with one manufacturer, one retailer, a capacitated warehouse with the shared capacity of $S = 5$. It is assumed that the demand functions of each product would be as follow.

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

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

Table 3. Optimal values under integrated scenario

$Z(P_1,P_2,\theta_1,\theta_2,S_1,S_2)$	P_1	P_2	θ_1	θ_2	S_1	S_2
1.514182834	**4**	**13**	**0.14**	**0.11**	**3**	**2**

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 two competitive supply chains are seen in Table 2.

The optimal values under integrated scenario are as follows in Table 3.

6. CONCLUSION

In this paper, a queueing-game model is developed for positing OPP in two competitive supply chains. The problem is considered in both integrated scenario (shared capacity model) and competition scenario (Stackelberg queueing-game model). Overall, DPD is more attractive when the semi-finished items can be provided to the manufacturer on demand, when customers are tolerant of a range of product characteristics, and when the demand on the manufacturer is not heavy. It is therefore vital for the manufacturer to understand how sensitive customers are to being able to precisely define the finished product, what demand level is expected, and the ability of their manufacturer to provide semi-finished items for customization. Developing more queueing-game model with different assumption about game strategy among multi-product competitive supply chains the can be considered as future research possibilities.

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APPENDIX A

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

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

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

(A.1)

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

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

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

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

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

APPENDIX B

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

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

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