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ORIGINAL ARTICLE

Price, delivery time, and capacity decisions in an M/M/1 make-to-order/service system with segmented market

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Abstract Speed and price are the two most important factors in customer satisfaction and business success in today's competitive environment. Time-based product differentiation and segment pricing have provided firms with a great opportunity to profit enhancement. This paper presents a coding system for pricing/queuing models in the literature. In this article, a service/make-to-order firm with heterogeneous price and delivery time-sensitive customers as an M/M/1 queuing system is analyzed. The firm uses customers' heterogeneity to create market segments. Products offered to each segment differ only in price and delivery time. The objective of this profit-maximizing firm is to determine optimal price, delivery time, and capacity for different market segments. Moreover, solving this problem can help to strategic decision making about supply chain decoupling point. An approach based on uniformization and matrix geometric method so as to calculate the distribution of low-priority customers' time in system is developed. Then, the proposed pricing/queuing model is implemented by a numerical study and firm's optimal decisions under shared and dedicated capacity strategies are analyzed and the effect of capacity costs and product substitution is studied. Finally, we have shown how firm's decisions are influenced by market characteristics, capacity costs, and operational strategies.

Keywords Time-based product differentiation · Pricing · Capacity management · Delivery time guarantees · Queuing systems

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1 Introduction

An effective way to maintain customer responsiveness and to enhance demand is through time-based product differentiation and segment pricing (Boyaci and Ray [4]). Offering products which are different only in delivery times and prices is a common strategy in markets with heterogeneous price and time-sensitive customers. Many companies, especially in service and make-to-order (MTO) industries, are using delivery time guarantees as their marketing strategy. Since shorter delivery times allow firms a price premium, they try to benefit from customers' sensitivity to speed. Adopting time-based product differentiation brings capacity-related issues to the forefront because speed of product delivery is directly influenced by a firm's capacity.

Companies that offer different products should decide whether a given product is available to all customers or distinct groups. For example, FedEx quotes different logistic services with different guaranteed delivery times to every customer willing to pay its price. Customers select the appropriate option based on their preferences for speed and willingness to pay. In this case, the menu of products offered is substitutable and demands are dependent. On the other hand, the price and delivery time combinations that Dell offers to government and health care corporations are different from those offered to individuals. Dell decides on a product's availability to each market segment, and customers have no choice. In this case, options are non-substitutable, and the demand from each segment is independent from others.

As a firm's marketing decisions are closely linked to its operation strategies, time-based product differentiation would have a direct influence on operational systems that produce and deliver these products. A natural question that comes to mind is whether firms differentiate systems used for production and delivery of different products or not. In other words, companies should decide on using shared or dedicated capacities.

The last two decades have observed significant research progress on the interaction of pricing and operations. This literature falls into two fundamental categories: pricing/inventory models and pricing/queuing models. In the first case, prices are determined jointly with inventory decisions or based on current inventory levels. In the second case, prices are used to control the arrival rate to a queue or queues and may or may not be set based on the current queue length (Ray and Jewkes [27]). Here, we have classified pricing/queuing models based on two general specifications: problem definition and modeling assumptions. A coding system is proposed in Table 1 and models available in recent literature are coded based on this system in Table 2. Among these pricing/queuing literatures, the closest works to ours are by Boyaci and Ray [4] and Sinha et al. [29]. Boyaci and Ray [4] studied a firm using dedicated facilities to serve two customer classes with different delivery time guarantees and at different prices. They modeled mean demand from each customer class as a linear function of its own price and delivery time as well as price and delivery time quoted to the other class. Our demand function is more general and uses different sensitivities (to price and time) for each class of customers. Besides, we consider two different operational strategies (shared and dedicated). Sinha et al. [29] consider a firm which uses shared capacities and delay dependent priority discipline to serve existing (primary class) and new customers (secondary class).

An outline of the remainder of this paper is as follows. In Section 2, the problem is defined more precisely. Section 3 is dedicated to the mathematical formulation of our model. Computational results are discussed in Section 4. We conclude the paper in Section 5.

2 Statement of the problem

According to the new business model of Internet/telephone ordering and quick response time requirement, MTO business model is growing quickly. We consider an MTO or a service firm that serves customers with different sensitivities to price and delivery time. The firm uses customers' heterogeneity to create market segments and offers them different prices and delivery times for the same product. For simplicity, we assume there are two classes of customers, express customers—who are more time sensitive and are willing to pay a price premium—and regular customers who are more price sensitive and are willing to accept a longer delivery time for a price discount than a shorter delivery time. Moreover, solving this problem can help strategic decision making about supply chain decou-

Table 1 Coding system proposed for classification

Problem Definition			Modeling assumptions		
Market	Monopolistic	Mo	Objective function	Profit maximization	MxP
	Competitive	Co		Value maximization	MxV
Customers	Homogeneous	Hm	Constraints	Delivery time reliability	DTR
	Heterogeneous	Ht		Customer's utility	CU
Pricing	Internal (transfer)	In		Expected waiting time	EWT
	External	Ex	Decision variables	Price	P
Operation strategy	Shared capacity	ShC		Capacity	C
	Dedicated capacity	DeC		Delivery time	D
Product differentiation	With	W		Other	O
	Without	WO	Queuing system	M/M/1	MM1
Product substitution	Substitutable	S		Other	O
	Non-substitutable	NS	Demand	Linear	L
				Nonlinear	NL
			Cost	Capacity	CC
				Operating	OC
				Delay	DC

Table 2 Classification of reviewed article

Item no.	Author(s)	Article's code (problem definition/modeling assumptions)
1	Mendelson [17]	Mo/Hm/In/DeC/SP/NS/MxP&MxV//P&C/O/L/CC&DC
2	Dewan and Mendelson [6]	Mo/Ht/In/ShC/SP/NS/MxV//P&C/MM1/L/CC&DC
3	Mendelson and Whang [18]	Mo/Ht/In/ShC/MP/NS/MxV//P&C/MM1/L/DC
4	Hill and Khosla [11]	Mo/Hm/Ex/DeC/SP/NS/MxP//P&D//NL
5	Stidham [32]	Mo/Ht/In/ShC/SP/NS/MxP//P&C/O/L/CC&DC
6	Li and Lee [15]	Co/Ht/Ex/DeC/SP/NS/MxP//P&C&O/MM1/NL
7	Lederer and Li [14]	Co/Ht/Ex/ShC/MP/NS/MxP//P&O/O/L/DC
8	So and Song [31]	Mo/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D&C/MM1/NL/CC&OC
9	Palaka et al. [20]	Mo/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM!/L/OC&DC
10	Ha [8]	Mo/Hm/In/DeC/SP/NS/MxP&MxV//P/O/L/OC&DC
11	Rao and Petersen [26]	Mo/Ht/In/ShC/MP/NS/MxP&MxV//P/MM1/L/OC&DC
12	So [30]	Co/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM1/L/OC
13	Van Mieghem [34]	Mo/Ht/Ex/ShC/MP/NS/MxP//P&O/MM1/L/OC&DC
14	Ha [9]	Mo/Ht/In/ShC/MP/S/MxV//P/O/L/OC&DC
15	Hall et al. [10]	Mo/Ht/Ex/ShC/MP/NS/MxP/EWT/P/L/
16	Boyaci and Ray [4]	Mo/Ht/Ex/DeC/MP/S/MxP/DTR/P&C&D/MM1/L/CC&OC
17	Mandjes [16]	Mo/Ht/Ex/ShC/MP/S&NS/MxP//P&C/MM1/L/CC&OC
18	Ray and Jewkes [27]	Mo/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM1//L/CC&OC
19	Allon and Federgruen [3]	Co/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM1//L/CC&OC
20	Afeche [1]	Mo/Ht/Ex/ShC/MP/NS/MxP/CU/P&O/MM1/L
21	Afeche and Mendelson [2]	Mo/Ht/Ex/ShC/MP/NS/MxP&MxV//P/MM1/L/DC
22	Katta and Sethuraman [13]	Mo/Ht/Ex/ShC/MP/NS/MxP//P&O/MM1/L/DC
23	Boyaci and Ray [5]	Mo/Ht/Ex/DeC/MP/S/MxP/DTR/P&C&D/MM1/L/CC&OC
24	Pekgun et al. [23]	Mo/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM1/L
25	Dobson and Stavrulaki [7]	Mo/Hm/Ex/DeC/SP/NS/MxP/CU/P&C&O/O/L/CC&DC
26	Allon and Federgruen [3]	Co/Ht/Ex/DeC&ShC/MP/NS/MxP/DTR/P&D/MM1/L/CC&OC
27	Pekgun et al. [22]	Co/Hm/Ex/DeC/SP/NS/MxP/DTR/P&D/MM1/L
28	Pangburn and Stavrulaki [21]	Mo/Ht/Ex/DeC&ShC/SP/NS/MxP/CU/P&C/MM1&O/L/CC&DC
29	Sinha et al. [29]	Mo/Ht/Ex/ShC/MP/NS//MxP/EWT/P&DC&O/MM1/L

pling point. Assumptions and decisions determined by the model are explained as follows.

2.1 Assumptions

- Demand from customer class i arrives according to a Poisson process with rate λ_i that depends not only on its own price and delivery time but also on price and delivery time quoted to the other class.
- Customers cannot observe the congestion in the firm, and their choices are based on the prices and delivery times offered.
- The time taken to serve each demand from class i is exponentially distributed with rate μ_i, therefore the service facility is modeled as an M/M/1 queuing system. We also assume that in SC, both service rates are equal to μ.
- Customers within each class are served based on FCFS priority discipline.
- Applying SC strategy, express customers are served based on preemptive priority discipline.
- All customers are served by the same service capacities hence capacity costs are equal for both classes.
- The operating cost the firm incurs for serving customers of either class is equal.
- Delivery time is predetermined and fixed for regular customers.

2.2 Decisions

- Which prices are to be offered for product/service to express and for regular customers.
- Which delivery time is to be quoted to express customers.
- Using different capacity strategies, which service rates are to be used in order to meet the guaranteed delivery times with a determined service level.

We also investigate how these decisions are influenced by changes in capacity costs, capacity strategies, and product substitutability. According to the coding system presented in Table 2, our studied problem will be coded as: Mo/Ht/Ex/DeC & ShC/W/S&NS/MxP/DTR&EWT/P&C&D/MM1/L/CC&OC.

3 Problem formulation

This section is dedicated to mathematical formulation of model. The following notations are used for the mathematical formulation of our problem:

Sets and indices

i Customer classes' index i=1,2

Parameters

$2a$	Market size
β_p^i	Sensitivity of customer within class i to its own price
β_L^i	Sensitivity of customer within class i to its own guaranteed delivery time
θ_p	Sensitivity of demand to interclass price difference
θ_L	Sensitivity of demand to interclass price difference
C	Unit operating cost
A	Capacity cost
α	Service level

Variables

p_i	Price quoted to customers within class i
L_i	Delivery time guaranteed to customers within class i
μ_i	Mean service rate for customers within class i
λ_i	Mean arrival rate for customers within class i
T_{si}	Time in system for customers within class i

The mathematical formulation of the problem is as follows:

$$\text{Max} \sum_{i=1}^{2} p_i \times \lambda_i - \sum_{i=1}^{2} c \times \lambda_i - \sum_{i=1}^{2} A \times \mu_i \tag{1}$$

Subject to

Stability condition (2)

$$\Pr(T_{si} \leq L_i) \geq \alpha \qquad \forall i \tag{3}$$

$$L_1 < L_2 \tag{4}$$

$$p_i \geq 0, \mu_i \geq 0, L_1 \geq 0 \tag{5}$$

Objective function (1) maximizes a firm's profit. Constraint (2) is the stability condition for the M/M/1 queuing system used for a modeling service facility. Constraint (3) imposes that the time that each customer spend in the system (time in queue+service time) of a customer should not exceed the guaranteed delivery time related to his class with a probability of at least α. Constraint (4) assures that the guaranteed delivery time for express customers be shorter than regular customers. According to assumptions in Section 2.1., demand from customer class i arrives according to a Poisson process with rate λ_i, which depends not only on its own absolute price and delivery time but also on its price and delivery time quoted relative to the other class. Then, the firm can attract new customers by reducing price and/or by offering shorter delivery times. The price and/or delivery time reduction for one class can also induce customers to switch preferences. It is assumed that customers cannot observe the congestion levels of the firms, and their choices are only based on the prices and delivery times announced by the firms. The demand rates are modeled using the linear functions (Eq. 6), inspired by Tsay and Agrawal [33], Boyaci and Ray [4]:

$$\lambda_i = \begin{cases} \lambda_1 = a - \beta_p^1 p_1 + \theta_p(p_2 - p_1) - \beta_L^1 L_1 + \theta_L(L_2 - L_1), i = 1 \\ \lambda_2 = a - \beta_p^2 p_2 + \theta_p(p_1 - p_2) - \beta_L^2 L_2 + \theta_L(L_1 - L_2), i = 2 \end{cases} \tag{6}$$

This demand model (Eq. 6) also confirms the effects of price and time differentiation on the demand rates: one extra unit of price differentiation decreases the demand rate from express customer and increases that from regular customers by the same amount, while one extra unit of time differentiation increases the demand rate from express customers and decreases that from regular customers by the same amount (Jayaswal et al. [12] and Sachin Jayaswal [28]). Constraints (2) and (3) can be written as

$$\lambda_i < \mu_i \qquad \forall i \tag{7}$$

$$\Pr(T_{si} \leq L_i) = 1 - e^{(\lambda_i - \mu_i)L_i} \geq \alpha \qquad \forall i \tag{8}$$

while using dedicated capacities and as

$$\lambda_1 + \lambda_2 < \mu \tag{9}$$

$$Pr(T_{si} \leq L_1) = 1 - e^{(\lambda_1 - \mu)L_i} \geq \alpha \qquad i = 1 \tag{10}$$

while using shared capacities. For regular customers, a closed form expression for distribution of time in a system does not exist. We describe the continuous time Markov chain model for an SC system in Section 3.1. Steady state probabilities are computed using the matrix geometric method (MGM). Ramaswami and Lucantoni [24] and Neuts [19] presented an algorithm based on uniformization to derive the complimentary distribution function of the stationary waiting times in quasi birth and death (QBD) processes. We adopt their algorithm to derive T_{s2}.

3.1 The Markov chain

Consider the continuous time Markov chain $\{(i,j), i \geq 0, 0 \leq j \leq M\}$, where i (the level) and j (the interlevel state) are respectively the number of low and high priority customers in the system. The generator matrix of this QBD process Q is given as

$$Q = \begin{bmatrix} B_{0,0} & A_0 & 0 & 0 & \dots \\ A_2 & A_1 & A_0 & 0 & \dots \\ 0 & A_2 & A_1 & A_0 & \dots \\ 0 & 0 & A_2 & A_1 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

where

$$A_0 = \begin{bmatrix} \lambda_2 & 0 & 0 & \dots \\ 0 & \lambda_2 & 0 & \dots \\ 0 & 0 & \lambda_2 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad A_2 = \begin{bmatrix} \mu & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

$$B_{0,0} = \begin{bmatrix} -(\mu+\lambda_2) & \lambda_1 & 0 & \dots \\ \mu & -(\mu+\lambda_2+\lambda_1) & \lambda_1 & \dots \\ 0 & \mu & -(\mu+\lambda_2+\lambda_1) & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} A_1 = \begin{bmatrix} -(2\mu+\lambda_2) & \lambda_1 & 0 & \dots \\ \mu & -(\mu+\lambda_2+\lambda_1) & \lambda_1 & \dots \\ 0 & \mu & -(\mu+\lambda_2+\lambda_1) & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

Submatrices A_0, A_1, A_2, and $B_{0,0}$ show transitions from level i to level i+1, transitions within level i>1, transitions from level i to level $i-1$ and transitions within level i=0, respectively.

3.2 Stability conditions

Let $A = A_0 + A_1 + A_2$. We have

$$A = \begin{bmatrix} -\mu & \lambda_1 & 0 & \dots \\ \mu & -(\mu+\lambda_1) & \lambda_1 & \dots \\ 0 & \mu & -(\mu+\lambda_1) & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

It is obvious that A is a generator matrix and its associated stationary distribution $\pi = [\pi_0, \pi_1, \dots, \pi_M]$ is driven as a solution to πA=0 and $\pi 1$=1.

3.3 The stationary distribution

Let $x = [x_0, x_1, x_2, \dots]$ be the stationary distribution associated with the Markov chain such that $x1$=1 and xQ=0.

From the matrix geometric theorem we know that

$$x_{i+1} = x_i R, \qquad i \geq 0$$

where R is the minimal nonnegative solution to the matrix quadratic equation

$$A_0 + RA_1 + R^2 A_2 = 0$$

The matrix R can be computed very easily using the iterative approach presented by Ramaswami and Lucantoni [25] and Neuts [19].

The boundary vector x_0 is obtained from

$$x_0 \left(B_{0,0} + RA_2 \right) = 0$$

We then normalize it by

$$x_0 (I - R)^{-1} e = 1$$

3.4 Computing regular customers' time in system

Based on the approach presented by Ramaswami and Lucantoni [24] and Neuts [19], the probability that a regular customer arriving to the system at an arbitrary time will wait longer than x units is equal to

$$\Pr(T_s > x) = \sum_{n=0}^{\infty} d_n e^{-\theta x} \frac{(\theta x)^n}{n!}$$

where $\theta = \max_{1 \leq j \leq m} - (A_0 + A_1)_{jj}$ and

$$d_n = \pi_0 (I - R)^{-1} R H_n e$$
$$H_0 = I \qquad H_{n+1} = H_n \widehat{A}_1 + R H_n \widehat{A}_2$$

where

$$\widehat{A}_1 = \frac{1}{\theta}(A_0 + A_1) + I \qquad \widehat{A}_2 = \frac{1}{\theta} A_2$$

Table 3 Values of parameters

PDSM		TDSM		β_p^1	β_p^2	β_L^1	β_L^2	A	a	c	α	L_2
θ_p	θ_L	θ_p	θ_L									
25	10	10	25	30	40	45	25	15	1000	3	0.99	3

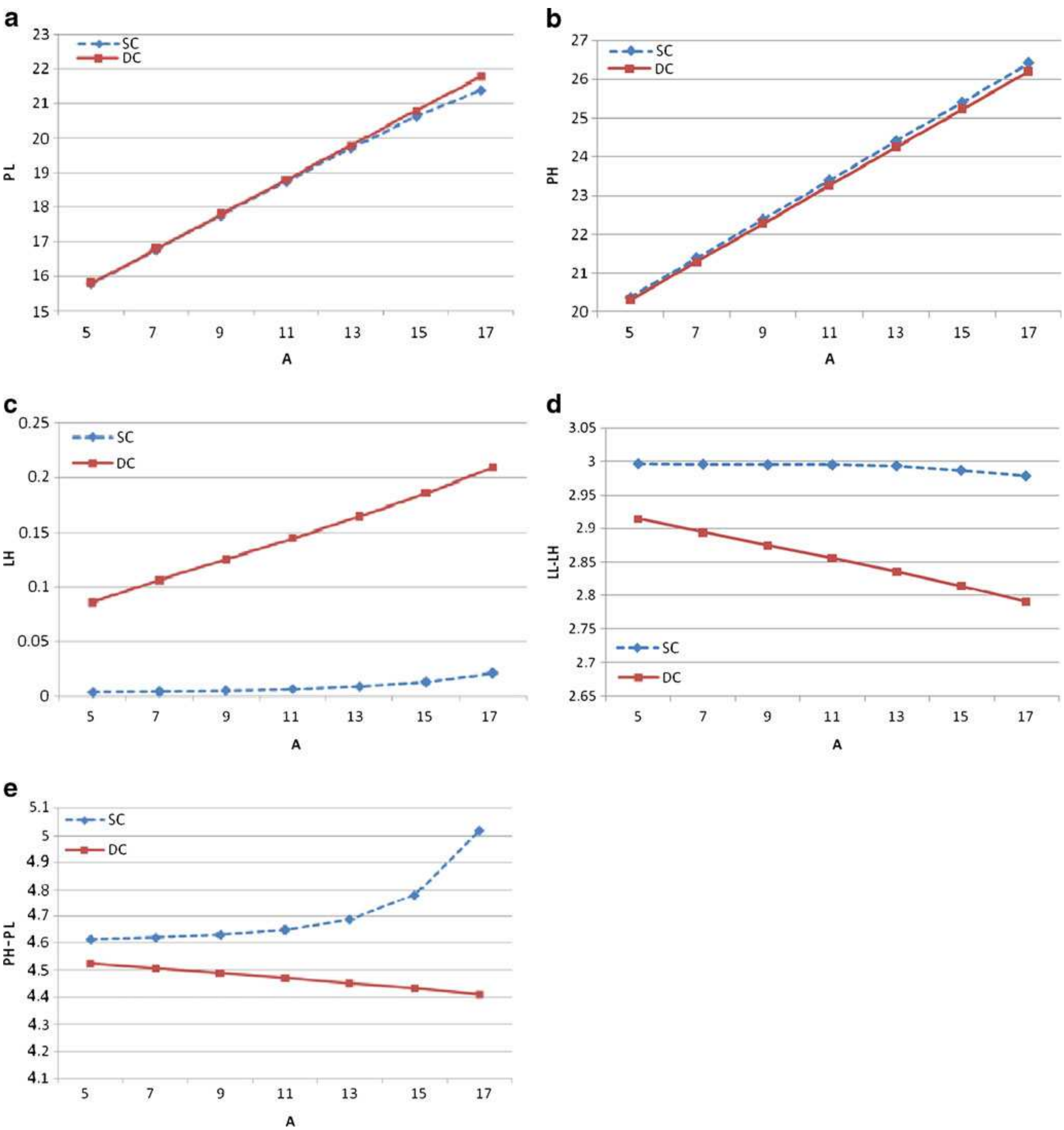

Fig. 1 The effect of capacity cost increase on **a** prices offered to regular customers, **b** prices offered to express customers, **c** delivery time offered to express customers, **d** delivery time difference, and **e** price difference, in a time difference-sensitive market

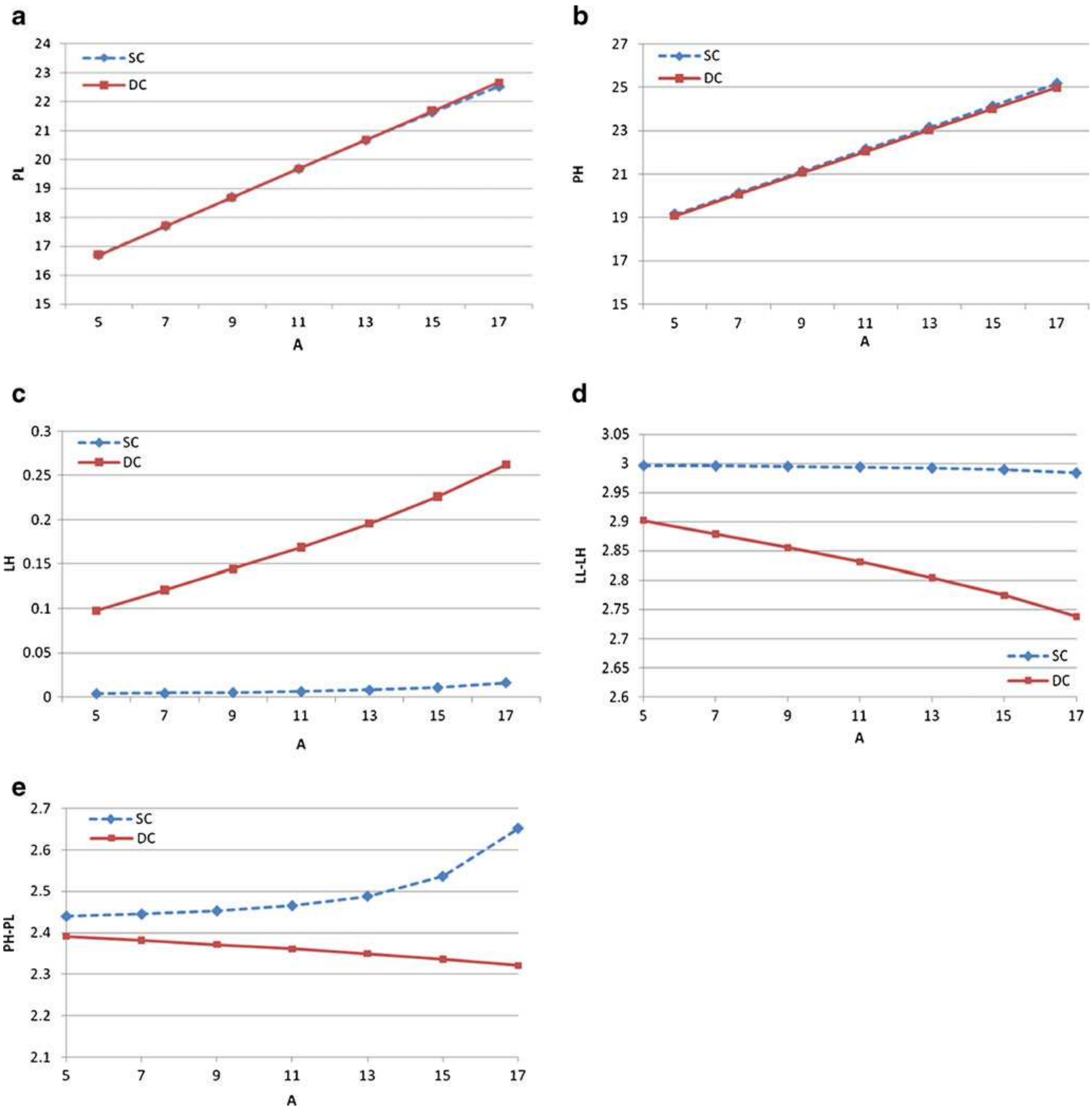

Fig. 2 The effect of capacity cost increase on **a** prices offered to regular customers, **b** prices offered to express customers, **c** delivery time offered to express customers, **d** delivery time difference, and **e** price difference, in a price difference-sensitive market

Now we can rewrite constraint (3) for regular customers as

$$\Pr(T_{si} < L_2) = 1 - \sum_{n=0}^{\infty} e^{-\theta x} \frac{(\theta x)^n}{n!} \pi_0 (I - R)^{-1} R H_n e > \alpha, \quad i = 2$$

4 Numerical examples

In this section, we illustrate how a firm's decisions relate to the capacity cost and operational strategies and present the optimal solution for a variety of parameter settings. Parameters θ_{L} and θ_p are assumed to be different for time difference-sensitive markets (TDSM) and price difference-sensitive markets (PDSM). Parameter values are presented in Table 3.

To study the effect of capacity costs on a firm's optimal decisions, we solved the problem for A=5, 7, 9, 11, 13, 15, 17. The results for TDSM, PDSM, and non-substitutable products (θ_p=θ_L= 0) are respectively illustrated in Figs. 1, 2, and 3.

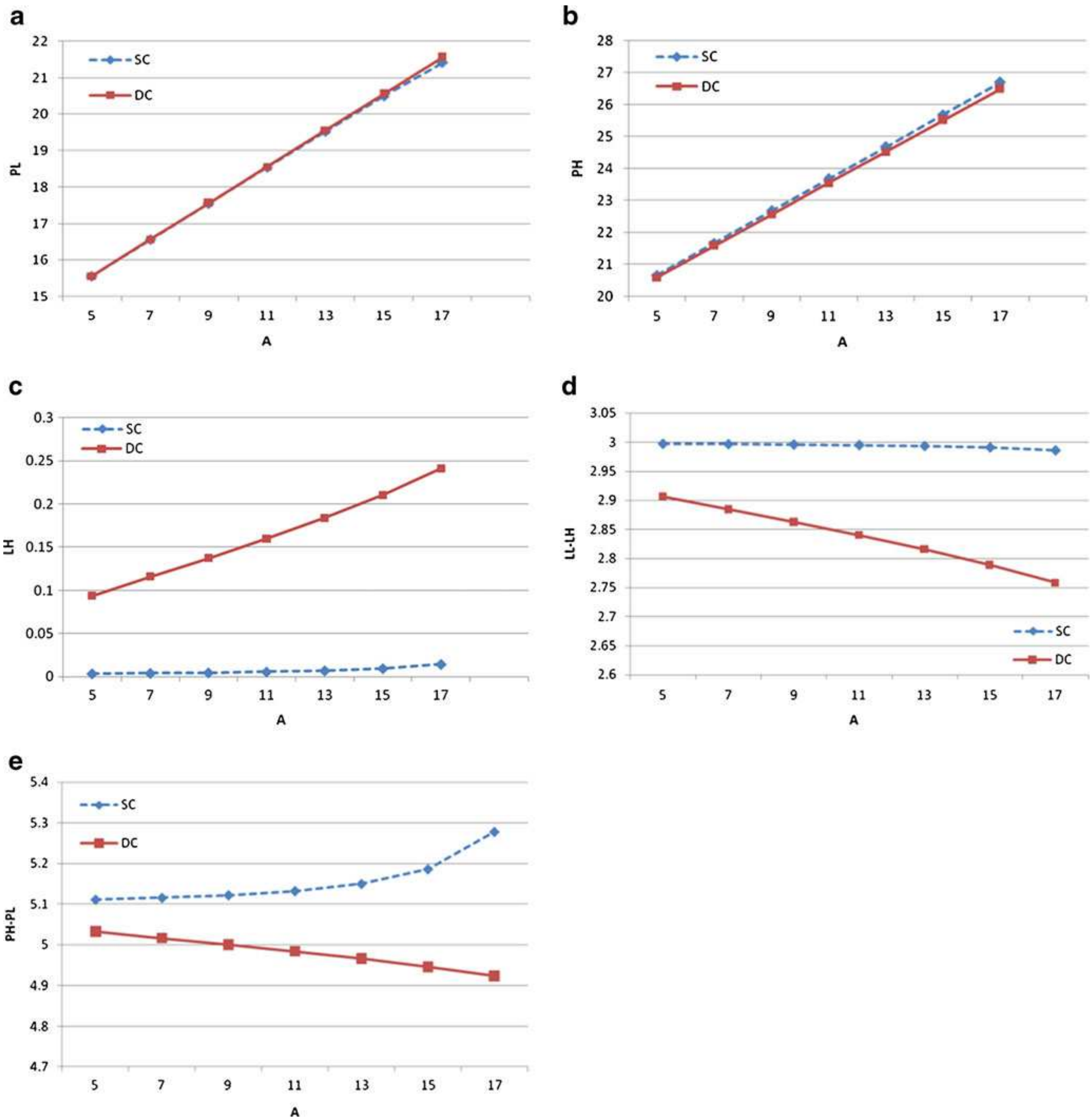

Fig. 3 The effect of capacity cost increase on **a** prices offered to regular customers, **b** prices offered to express customers, **c** delivery time offered to express customers, **d** delivery time difference, and **e** price difference for non-substitutable products

As shown above, irrespective of market characteristics, for a firm using shared capacities, the optimal decision in reaction to an increase in marginal capacity cost is to increase the delivery time for express customers and prices for both classes. Obviously, when the capacity costs increase, it will not be beneficial for the firm to expand its capacities, therefore the service rate decreases and the delivery time will increase. The delivery time and the prices should be set so that the delivery time differentiation decreases and the price differentiation increases. For a firm

Table 4 Results for A=15 in TDSM, PDSM, and non-substitutable cases

	TDSM		PDSM		Non-substitutable	
	SC	DC	SC	DC	SC	DC
p_1	25.12542	25.32329	23.9578	23.8629	25.45487	25.32329
p_2	20.64079	20.5625	31.05279	21.63891	20.44629	20.5625
L_1	0.284547	0.45783	0.31452	0.49139	0.06384	0.45783
μ_1	339.6329	229.7573	335.4478	240.8582	334.64511	229.7573
μ_2		104.0351		91.49204		104.0351
Profit	1,898.76	1,697.669	1,701.837	1,520.929	1,837.234	1,697.669

using dedicated capacities, optimal decisions are similar to the ones in a shared capacity strategy, but delivery time and prices should be set so that the delivery time differentiation and price differentiation decrease.

The results for A=15 in TDSM, PDSM, and non-substitutable cases are reported in Table 4. Tables 5 and 6 illustrate the effect of product substitution and capacity strategies on a firm's optimal decisions and profit.

Product substitution will lead to a decrease in an express product's price and an increase in a regular product's price and express product's delivery time (see Table 4). In other words, when products are substitutable, the price and delivery time differentiations are less than non-substitutable cases (see Table 4). Besides, using dedicated capacities in TDSM and PDSM, μ_1 is larger and μ_2 is smaller compared to non-substitutable case.

As presented in Table 5, using shared capacities to serve different customer classes will cause an increase in an express product's price and a decrease in a regular product's price and express product's delivery time. In other words, when capacities are shared, price and delivery time differentiations are more than dedicated cases.

5 Conclusions

According to the new business model of Internet/telephone ordering and quick response time requirement, the MTO business model is growing quickly. In this article, the authors have studied an MTO service firm that serves nonhomogeneous price and time-sensitive customers. The firm uses nonhomogeneity and differentiates its product based on the delivery time. Therefore, different delivery times and prices are offered to different customer classes. In this study, the firm modeled as an M/M/1 queuing system. Then, an approach based on uniformization and MGM so as to calculate the distribution of low-priority customers' time in a system is developed. A numerical example is provided and a firm's optimal decisions under shared and dedicated capacity strategies are analyzed. The effect of capacity costs and product substitution is studied. Consequently, solving this queuing–pricing problem can help strategic decision making about the supply chain decoupling point. This study modeled the firm as an M/M/1 queuing system. More general systems like G/G/1 and implementation in a real case study such as an electronic product supply chain can also be a topic of future studies. Moreover, considering competitive markets would be a challenging problem.

Table 5 Effect of product substitution on a firm's optimal decisions

	TDSM		PDSM	
	SC	DC	SC	DC
p_1	Decrease	Decrease	Decrease	Decrease
p_2	Increase	Increase	Increase	Increase
p_1–p_2	Decrease	Decrease	Decrease	Decrease
L_1	Increase	Increase	Increase	Increase
L_1–L_2	Decrease	Decrease	Decrease	Decrease

Table 6 Effect of using shared capacities on a firm's optimal decisions

	TDSM	PDSM	Non-substitutable
p_1	Increase	Increase	Increase
p_2	Decrease	Decrease	Decrease
p_1–p_2	Increase	Increase	Increase
L_1	Decrease	Decrease	Decrease
L_1–L_2	Increase	Increase	Increase

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