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An analytical framework for evaluating the value of enhanced customisation: An integrated operations-marketing perspective

Hartanto Wong^a and Daniel Eyers^b

^a*CORAL, Department of Business Studies, Aarhus School of Business, University of Aarhus, Fuglesangs Allé 4, DK-8210 Aarhus V, Denmark*

^b*Cardiff Business School, Cardiff University, Column Drive, Cardiff CF10 3EU, United Kingdom*

Abstract: In this paper we present a formal approach to evaluate the value of enhanced customisation. The suggested approach is based on a new perspective addressing the important alignment between the operations and marketing functions, under which we are able to obtain a more holistic understanding of the extent to which enhanced customisation may influence profitability. The model we developed captures the interaction between several factors including the inventory level, number of product variety, price, and delivery lead time. The numerical findings provide insights regarding some important aspects that may inhibit as well as facilitate the progress towards the manufacturing concept with a greater degree of personalised offerings.

Keywords: Mass Customisation; Postponement; Integrated operations-marketing problem

1. Introduction

It can be argued that one of the most difficult problems faced by manufacturers nowadays is the need to present an ever more valuable service to customers whilst at the same time cutting delivery times and total operating costs. One attractive technique of increasing the value or utility of a manufactured product can be seen as product customisation, whereby products are tailored to the individual requirements of the customer. This has triggered the new manufacturing paradigm that is called *mass customisation* (MC). This new paradigm replaces *mass production* which is viewed as no longer suitable for today's competitive environment (Pine 1993). The concept has already received considerable attention in the literature since its identification by Davis (1987) and the influential book by Pine (1993), however as yet failed to fully achieve the originally envisaged potential (Piller 2004).

MC combines the best of the craft era, where products were personalised but at high cost, with the best of Mass Production, where products were affordable but highly standardised

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(Fralix, 2001). In an ideal world, MC will ultimately achieve a situation in which firms are able to provide customised products at a comparable price and speed of equivalent standardised offerings. However, empirical evidence suggests a more pragmatic view in that the customisation is not 'free' and need to be traded-off against lead time, cost, and other factors (McCutcheon et al. 1994, Squire et al. 2006). Hence, in deciding the right customisation level, firms would certainly need to consider these trade-offs, which essentially entail many aspects pertinent to the operations (production-inventory) as well as marketing functions.

Whilst it is evident that the current state of mass customisation is achievable through the adoption of innovative technologies and techniques such as flexible manufacturing systems, modularization, postponement and e-commerce, our literature review suggests that most of the extant academic literature tends to focus heavily on the evaluation of such technologies and techniques in the context of operations without adequate consideration being paid to the marketing factors. Postponement, for example, has been extensively studied in recent years and shown as an attractive means to accommodate MC. The main benefit of postponement is the possibility to lessen the total inventory cost. This is primarily achieved by the reduction of demand forecast errors and also by delaying expensive operations that enables companies to maintain the bulk of its inventories in the cheaper and/or pre-customized form (Lee et al. 1993, Lee 1997, Swaminathan and Lee 2003). Typically, the value of postponement is evaluated on the basis that the demand rate from customers is assumed to be given (i.e. the consequences of factors such as price, lead time and product characteristics on the customer purchase choice are ignored).

We argue that such analysis focusing solely on the operations aspects would be deficient. When firms move from mass production to mass customisation, the alignment of both the operations and marketing decisions is undeniably important. It would be legitimate to question whether, for example, there would be an effect of longer lead times on customer willingness to buy, which will consequently influence the total profitability. Similarly, firms' decision on product price cannot be ignored. The product price must be optimized by taking into account product variety, inventory cost reductions, and the possible dissatisfaction of customers due to longer lead times.

Aware of the above discussed limitations, in this article we present a formal approach to evaluate the value of enhanced customisation by taking the operations-marketing interface into consideration. The model we developed captures the importance of operations and marketing decisions, which include the inventory level, number of product varieties, price, and delivery lead time.

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2 The rest of the paper is organised as follows. In the next section we present the literature
3 review and highlight the main contributions we make to the existing body of knowledge.
4 Section 3 presents the model. We describe how the integrated model is built up from the
5 marketing and production-inventory models. Section 4 presents and discusses our numerical
6 findings. Finally, we summarise the results in Section 5 and conclude with some suggestions
7 for further research.
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10 11 12 13 **2. Literature Review**

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15 Three streams of literature are relevant to our study. The first studies decisions made for
16 manufacturing products, mostly concentrated on the choice between MTS or MTO strategies.
17 The second considers production-inventory systems that accommodate mass customisation,
18 whilst the final stream analyses coordinated marketing and operations decisions. Our research
19 serves to integrate and extend this literature.
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23 Analytical models related to the decision of manufacturing products in a MTS or MTO
24 fashion are presented by several authors including Federgruen and Katalan (1999), Arreola-
25 Risa and DeCroix (1998), and Rajagopalan (2002). Federgruen and Katalan (1999) consider
26 systems where some products are made to stock while other product lines are made to order.
27 The primary focus of their paper is on the different strategies for deciding whether and when
28 to “interrupt” the production of MTS with MTO items and providing related insights.
29 Arreola-Risa and DeCroix (1998) study the optimality of make-to-order (MTO) versus make-
30 to-stock (MTS) policies for a company producing multiple heterogeneous products at a shared
31 manufacturing facility. The authors also discussed to what extent reducing manufacturing
32 lead time randomness helps a product to be produced for MTO. Similar work is presented in
33 Rajagopalan (2002) where the author considers a manufacturing setting faced with the
34 decision about which items to make to stock and which ones to make to order.
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38 There are numerous studies analyzing production-inventory systems that accommodate MC.
39 Relevant to our study are those particularly analysing the production and inventory systems
40 employing postponement or delayed product differentiation. There is a large body of literature
41 on postponement. We refer the reader to van Hoek (2001), Swaminathan and Lee (2003), and
42 Yang and Burns (2003) for a comprehensive review of research on postponement. Analytical
43 models measuring the costs and benefits of postponement are presented by Lee and Tang
44 (1997), Garg and Tang (1997), Swaminathan and Tayur (1998), and Aviv and Federgruen
45 (2001a and 2001b). However, these models ignore the effect of queuing at the production
46 facility. Gupta and Benjaafar (2004) consider the capacitated production system and model
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2 the system employing form postponement as a two-stage system. Another study incorporating
3 the queuing effect is by Su et al. (2005). In this paper, the authors compare two specific
4 configurations. In the first configuration products are produced after orders arrive (MTO
5 mode) and the second configuration represents the system employing form postponement.
6 More recently Wong et al. (2009) examine different postponement configurations
7 characterised based on the positioning of the differentiation point and the customer order
8 decoupling point. All these studies are common in that their analysis is focused on the
9 production-inventory system without considering any marketing factors. It is not surprising to
10 observe that their results are based on an assumption that demand and number of product
11 varieties are given, and that the evaluation is made based on a cost-minimisation strategy. In
12 this paper we consider both production-inventory as well as marketing factors and hence a
13 profit maximisation strategy is used instead of the cost-minimisation strategy.
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20 The final stream of research identified in this review concerns both operations and marketing
21 factors. For example, Li (1992) considers a situation in which customer utility is sensitive to
22 price, quality, and lead time with the supplier being able to control the production rate. The
23 author first analyses the single-firm problem and derived simple 'newsboy'-like formulas to
24 determine the optimal production/inventory policy and the optimal choice between make-to-
25 order and make-to-stock operations. The model is then extended to address multiple suppliers
26 who compete for demand based on delivery time. Palaka et al. (1998) study how the
27 interaction between lead time, capacity utilisation and price affect operational performance.
28 They model the firm's operations as an $M/M/1$ queue and treat demand as a linear function of
29 price and quoted lead time. Webster (2002) models a make-to-order system in which demand
30 rate is a function of price and lead time. He models the system as a queuing system and
31 allows the production rate to be changed dramatically. Yang and Geunes (2007) study a
32 combined strategic and operational level planning model that determines the best positioning
33 of a product with respect to price and promised lead time. They consider a continuous review
34 inventory replenishment system, where two types of lead times, procurement and sales lead
35 times influences both cycle stock and safety stock costs. Although they consider multiple
36 factors affecting demand, it is obvious that their analysis treats each of these factors
37 independently. This is different from our analysis in which we are interested in capturing the
38 interplay of price, degree of customisation and quoted lead time.
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47 From the literature assessment several papers were identified as studying the coordination of
48 marketing and operations decisions similar to ours. De Groote (1994) analyses the joint
49 problem of marketing/manufacturing coordination with the focus being on the exploration of
50 cross-functional implications of the flexibility of manufacturing processes. In this work, two
51 complementary problems were formulated: the marketing choice of the breadth of the product
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2 line, and the manufacturing choice of the flexibility of the production process. Most notably,
3 this work identified that the decentralised solution of the two problems typically yields a
4 suboptimal solution. In a related study, Dobson and Yano (2002) assessed the situation faced
5 by a manufactures which experienced demand that is not only influenced by price, but also
6 lead time. In this scenario, the firm must decide which products to offer, how to price them,
7 whether each should be made to stock or made to order, and how often to produce them. In
8 the study, several assumptions are made. Firstly, the products are assumed to originate from a
9 single manufacturing facility where setup times introduce diseconomies of scope and setup
10 costs introduce economies of scale. Additionally, deterministic demand is assumed which is
11 linearly decreasing in price and lead time. However, in contrast to both De Groot (1994) and
12 ours, the models presented in Dobson and Yano (2002) fail to consider how the number of
13 products offered influence customers' purchase decision. Furthermore, in comparison to the
14 above mentioned two papers, the focus of our analysis in this paper is very different in that
15 we are particularly keen to make comparisons between different manufacturing
16 configurations in the context of Mass Customisation.
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24 Mass Customisation has been a widely explored concept, for which this review serves only to
25 identify the most pertinent discussions. One such study is that of Jiang et al. (2006), who
26 compare two configurations: Mass Customisation and Mass Production. In their model, the
27 Mass Customisation system consists of two stages: the initial build-to-stock phase and the
28 final customise-to-order phase. By contrast, the Mass Production system has only a single
29 stage that builds products with pre-determined specifications to stock. Jiang et al. (2006)
30 characterise three possible benefits of Mass Customisation: (i) the gained surplus from
31 offering each customer her ideal product; (ii) extra revenue from price discrimination; and
32 (iii) reduced costs due to risk pooling. Our analysis is different from theirs mainly in the
33 following respects. Firstly, in addition to the make to stock and build to order systems that
34 represent Mass Production and Mass Customisation, we also consider a make to order system
35 accommodating the pure customisation strategy. Secondly, their model ignores the effect of
36 queuing at the production facility while we explicitly model the queuing effect as a result of
37 considering a capacitated production facility.
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44 The model presented in this paper builds on earlier work (Wong and Naim 2010) in which an
45 integrated operations-marketing model is used to re-examine the benefits of postponement.
46 The use of such an integrated model reveals a number of different aspects associated with
47 postponement costs and benefits other than inventory costs typically considered when using
48 the more traditional production-inventory model. In this paper the model is extended to
49 particularly accommodate a wider range of customisation level.
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Finally, Alptekinoglu and Corbett (2009) analyse the trade-off between the enhanced ability to meet individual preferences and the longer lead time associated with customised products. They develop a solution method to characterise the optimal product line design allowing a set of customised and standard products. While the modelling framework used in our paper is similar to theirs, our analysis is different in the following aspects. Firstly, while they consider two strategies, namely a MTS system producing standard products and a MTO system producing customised products, we consider three configurations that include the DD configuration employing postponement in addition to the MTS and MTO configurations. As postponement is a quite important strategy to accommodate Mass Customisation, we believe that the inclusion of the DD configuration will give more insights into our analysis. Secondly, while the main objective of their paper is to determine the optimal product line design strategy that allows a combination of the MTS and MTO products, our objective is to assess the relative merit of the three manufacturing configurations. We devise an optimisation procedure for each configuration so that comparisons of the three configurations can be made based on their respective best performances. Furthermore, though their market demand model assuming any continuous distribution is more general than our model based on a uniform distribution, their production-inventory model is more restricted as it is based on the assumption of zero product proliferation cost and identical manufacturing costs while we consider a product proliferation cost for the MTS and DD configurations and allow non identical manufacturing costs for the three configurations. Moreover, as most of the existing studies do, their model assumes the optimality of complete market coverage. Our model is more generic by virtue of its capability to accommodate partial market coverage.

3. The model

In this section, we provide an overview of the generic model framework that underlines our analysis. In Section 3.1 we formally present three different manufacturing configurations that will be compared. Section 3.2 presents the general market demand model. In Section 3.3 we outline the production-inventory models associated with the three manufacturing configurations. Section 3.4 presents an integrated framework in which the optimization problem is formulated as a joint marketing and production-inventory decision making problem.

3.1 The description of manufacturing systems

We consider three different manufacturing configurations, each having a different customisation level. A graphical depiction of the three configurations is shown in Figure 1. Further details on the operational description of the three configurations are as follows.

Figure 1 should be placed around here

Configuration I: Make-to-stock system (MTS)

In the first configuration, a set of finished products are produced in a make-to-stock (MTS) mode, with items produced in advance of actual demand and resultantly held in stock. In these circumstances, demand will be satisfied from the stock (unless the stock is empty), and all shortages backlogged. This configuration is modelled as a one stage production-inventory system. In this configuration, the manufacturer offers N finished products (N is a decision variable), indexed by $i = 1, 2, \dots, N$. We denote Λ as the total demand rate. End customer demand of product i arrives in single units according to a Poisson process with rate λ_i , and as we allow partial market coverage, $\Lambda \geq \sum_{i=1}^N \lambda_i$. We assume that the processing times are i.i.d. random variables and exponentially distributed with rate $1/\mu$. For stability, we require that $\Lambda/\mu = \rho < 1$. We assume that a base-stock policy is used for the inventory control. Let S_i denote the base stock level for finished product i . Furthermore, changeover times between products are assumed to be negligible.

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Configuration II: Mass customisation with delayed differentiation (DD) The second configuration accommodates what so-called “delayed differentiation” (DD) or postponement. We model this configuration as a two stage production-inventory system, with Stage-1 producing a component that is common for all finished products and Stage-2 differentiating the finished products. This configuration maintains stocks of a generic component and differentiates the finished products only after demand is realised. Hence, manufacturing

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occurs in a make-to-stock mode in Stage-1 and a make-to-order mode in Stage-2. It is notable to mention here that in both configurations, customers have the opportunity to choose their preferred product based on a set of product offerings pre-specified by the manufacturer. As producing to stock becomes costly when the number of products is large, one would reasonably expect that DD is capable to offer more product variety than MTS. But this does not include the cost associated to a longer waiting time experienced by customers, since DD does not hold an inventory of finished products.

We assume that the processing times for Stage 1 and Stage 2 are i.i.d. random variables and exponentially distributed with rates $1/\mu_1$ and $1/\mu_2$ respectively and that $1/\mu_1 + 1/\mu_2 = 1/\mu$. We define b ($0 < b < 1$) as the fraction of the mean total processing time consumed by the generic component. Thus, we may write $\mu_1 = \mu/b$ and $\mu_2 = \mu/(1-b)$. Small b values represent early postponement while large b values represent late postponement. Again, we require that $\lambda/\mu_j = \rho_j < 1$ for $j=1$ and 2 , where ρ_j is the j -stage utilisation rate. The base stock level for generic components is denoted as S_0 , while the stock level for finished products is zero for all $i = 1, 2, \dots, N$. Here we also assume negligible changeover times.

Configuration III: Custom Manufacturing (CM)

Finally, the third configuration termed as Custom Manufacturing (CM) accommodates a full customisation strategy. The CM configuration is actually an MTO configuration in which customised finished products are manufactured through a single stage process. The main difference between CM and the other two configurations is that CM allows an individual customer to purchase a product based on her own specification. An example would be the customisation of a product to their own physical measurements (e.g. custom clothing, etc), rather than based on a pre-specified set of product offerings. Hence, the limit of the number of product variety could be as large as the population size of the market. To be competitive, this configuration would definitely require the support of advanced manufacturing technologies that are able to address the responsiveness and flexibility issues prevalent in the traditional MTO environment. The promising development of new techniques of manufacturing, such as found in *Rapid Manufacturing*, should be seen as a potential enabler of CM. Rapid Manufacturing (RM) is a term used to name a group of additive fabrication technologies that have evolved from Rapid Prototyping (RP). The main concept behind RM is that any 3D shape can be fabricated as an ordered set of 2D layers with a discrete thickness, with a key advantage being the direct production of goods without any tooling (such as moulds or dies).

1
2 The absence of tooling not only simplifies the manufacturing process, it also removes large
3 fixed costs of production which inherently make traditional manufacturing processes such as
4 injection moulding financially impractical for custom, low volume production. Already, these
5 technologies are proving viable in many medical applications such as hearing aids, dental
6 aligners, etc. The very promising development of these technologies seems to be an important
7 catalyst for enhancing the viability of CM in the next few years (Bulkeley 2006, Eyers and
8 Wong 2009, Hopkinson et al. 2006, Judah 2009).

9
10 In the CM configuration, we assume that the processing times are i.i.d. random variables and
11 exponentially distributed with rate $1/\mu'$, where $\mu' \geq \mu$. This reflects our optimistic view in
12 that shorter manufacturing processing times (in comparison to MTS) are achievable through
13 the advancement of new manufacturing technologies. For stability, we require that $\Lambda/\mu' < 1$.

14
15 Let c_{MTS} , c_{DD} and c_{CM} denote the unit production cost for each of the manufacturing
16 configurations respectively. To reflect the costs of adopting innovation, we assume that the
17 direct cost of manufacturing is non-decreasing when we move along MTS, DD, and CM. This
18 is due to the fact that employing systems with greater innovation would require new
19 production processes to be setup and perfected. Formally, $c_{MTS} \leq c_{DD} \leq c_{CM}$. For each
20 configuration, the unit production cost is assumed to be identical for all finished products. Let
21 h denote the holding cost per unit per unit time for all finished products, and h_0 denote the
22 holding cost per unit per unit time for the generic component. For the MTS and DD
23 configurations there is a product proliferation cost K , incurred every time the manufacturer
24 offers a new product variant. This cost could include redesign, tooling and setup costs. The
25 linearity assumption of product proliferation cost in the number of products is in line with
26 common observation in the operations literature (Thonemann and Bradley 2002; Benjaafar et
27 al. 2004). To reflect the highly flexible feature such as offered by RM technologies, we
28 assume that there is no proliferation cost incurred for the CM configuration.

29
30 For MTS, the manufacturer makes simultaneous decisions regarding the number of product
31 varieties, their characteristics, base stock level of finished products, and price, maximising the
32 expected profit. Note that the decision on the base stock level will also influence the promised
33 lead time offered to customers. The DD manufacturer makes similar decisions as for the MTS
34 manufacturer except for the fact that they must decide on the base stock level of generic
35 components instead of finished products. For the CM manufacturer, the only relevant decision
36 is price. All the notations used throughout the paper are presented in Table 1.

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Table 1 should be placed around here

3.2 The market demand model

In this paper we base our marketing model on the locational model of customer choice. It is along the line of the spatial location model of Hotelling (1929) and its extensions by Lancaster (1990), and well established in the marketing and economic literature. Specifically, we evaluate a single manufacturing firm monopolistically serving a market with heterogeneous consumers over a single time period. In this model customer tastes are uniformly distributed over the closed interval of product space $[0, 1]$. All products are horizontally differentiated, with each characterised by a single point in that interval (quantified by a real number between 0 and 1). This can represent, for example, the size or colour attribute of the product. As Mass Customisation applications are generally characterised by customer tastes rather than product qualities, models based on horizontal differentiation are deemed to be more appropriate in comparison to vertical differentiation (Jiang et al., 2006). Products are offered with price p , assumed to be identical for all products. The uniform pricing scheme is reasonable when the products are horizontally differentiated in which qualities of products are at the same level. It is also a common marketing practice to charge the same price for the customised products even if different customers choose different options while customising (Syam and Kumar, 2006). Each customer buys one unit from the manufacturer and has her own ideal product represented by her location $\theta \in [0, 1]$. We assume that demands arrive according to a Poisson process and the total potential demand rate in the market is given by Λ . As noted during the literature assessment, our demand model is different from some others in that it captures the situation in which demand is not only sensitive to price and product characteristics, but also to delivery lead time. This allows us to better consider the situation for Mass Customisation in which many characteristic are relevant in the selection of a product. In this model we assume that the manufacturer commits to satisfy a lead time guarantee w for all product lines and maintain a service level of $1-\beta$ (i.e. delivery occurs within w time units with $1-\beta$ probability). Customers pay a linear transportation cost c_x per unit distance between their ideal product and the purchased product (c_x represents the intensity of customer preference). Furthermore,

customers also pay a linear delay cost c_w per time unit of delivery lead time. Higher values of c_x (c_w) mean customers are more sensitive to the deviation from their ideal products (the delay incurred).

The utility of customer at θ derives from buying product i with characteristic x_i , price p , and lead time guarantee w is given by

$$U(\theta, x_i, p, w) = \bar{r} - p - c_w w - c_x |\theta - x_i|, \quad (1)$$

where \bar{r} is a reservation price (in this model all consumers are assumed to have a common reservation price \bar{r} for their ideal product). In Equation (1) the customer's disutility of misfit relative to their ideal preference is expressed as $c_x |\theta - x_i|$, and the disutility of waiting is represented by $c_w w$. In each case, the consumer will select the product which maximises their utility. In the event that the utility is negative, the customer will not make a purchase. Product i is said to be the first choice of a given customer if it gives a non-negative utility to that customer and its utility is the maximum among all products offered by the manufacturer. Denote π_i as the *first choice probability* of product i , the demand rate for product i can be defined as $\lambda_i = \pi_i \Lambda$, $i = 1, 2, \dots, N$. As stated earlier, it should be underlined here that our model is not based on the assumption that only complete market coverage is optimal, which is commonly adopted by most of the existing models.

To identify the optimal design of the product line we use the well known optimality condition for the Hotelling's location model as also identified in de Groot (1994). That is, for a given N , the optimal product line has a simple structure: the market should be partitioned in segments of equal lengths, the characteristics of the products should correspond to the taste of the customers located in the middle of the segments, and the manufacturer should set prices as to make the customers located at the extreme of the segments indifferent between buying and not buying. To put it more formally, given that N is fixed, the optimal product characteristics can be determined from:

$$x_i^* = \frac{2i-1}{2N}, \quad i = 1, 2, \dots, N \quad (2)$$

For the case in which *complete market coverage* holds, given that N , w , c_w , and c_x are fixed, it is easy to show that the optimal price is equal to:

$$p^* = \bar{r} - c_w w - \frac{c_x}{2N}. \quad (3)$$

But since we remove the complete market coverage restriction, the optimal price expression given in (3) is no longer applicable. Instead, we now have to consider a trade-off in maximising revenue either by maximising market coverage (and setting a lower price) or increasing price with some loss in market coverage. Figure 2 can be used to explain such a trade-off. The figure illustrates an example of one product positioning. Following (1), the optimal product characteristic, x^* , is located in the middle of the segment. The green line shown in the figure represents the disutility distribution of customers when the price p_B is optimised under complete market coverage ($\pi_B = 1$). The other disutility function (shown in red) represents an alternative solution as a consequence of increasing the price to p_A leading to reduced market coverage ($\pi_A < 1$).

Figure 2 should be placed around here

Below we characterise the optimal price for the case where incomplete market coverage is considered. Given that N , w , \bar{r} , c_w , and c_x are fixed, the maximum revenue is obtained by setting the price at:

$$p^* = \begin{cases} \bar{r} - c_w w - \frac{c_x}{2N} & \text{if } \bar{r} - c_w w \geq \frac{c_x}{N}, \text{ or} \\ \frac{\bar{r} - c_w w}{2} & \text{if } \bar{r} - c_w w < \frac{c_x}{N}. \end{cases} \quad (4)$$

Proof: see Appendix.

Note that the expression in (4) is only valid for the MTS and DD configurations as N is a relevant decision variable. For the CM configuration, however, the optimal price can be determined using a different expression explained later in § 3.4.

From (2) and (4) new can now derive the first choice probability of product i :

$$\pi_i = \begin{cases} \frac{1}{N} & \text{if } \bar{r} - c_w w \geq \frac{c_x}{N}, \text{ or} \\ \frac{1}{N} - \frac{1}{2N^2} + \frac{\bar{r}}{2N c_x} - \frac{c_w w}{2N c_x} & \text{if } \bar{r} - c_w w < \frac{c_x}{N}. \end{cases} \quad (5)$$

3.3 The production-inventory model

In this section we present the evaluation model for each of the three configurations. The models are required to obtain relevant measures such as the expected inventory level and lead time that are dependent on the inventory decision.

For the MTS configuration:

In this paper we adopt the evaluation model of Buzacott and Shanthikumar (1993). For a given base stock level, the expected inventory for finished product i is given by:

$$I_i(S_i) = S_i - \left(\frac{\lambda_i}{\mu - \Lambda} \right) (1 - \hat{\rho}_i^{S_i}), \quad (6)$$

where $\hat{\rho}_i = \lambda_i / (\mu - \lambda_i)$ and $\lambda_{-i} = \sum_{j \neq i} \lambda_j$.

The probability that the order-fulfilment time will not exceed a quoted lead time w ($w \geq 0$) is given by:

$$\Pr[T_i(S_i) \leq w] = 1 - \hat{\rho}_i^{S_i} \cdot e^{-(\mu - \Lambda)w} \quad (7)$$

The manufacturer sets a minimum service level $1 - \beta$, where $0 < \beta < 1$ guaranteeing that the actual lead time will not exceed the promised lead time, i.e. $\Pr[T_i(S_i) \leq w] \geq 1 - \beta$. It is very straightforward to find that, for a given base stock level S_i , the manufacturer will be reasonably interested in setting the promised lead time such that the service constraint is binding. We can state:

$$w = \max \left(0, \frac{1}{\mu - \Lambda} (S_i \ln \hat{\rho}_i - \ln \beta) \right). \quad (8)$$

For the DD configuration:

We use the evaluation models derived in Gupta and Benjaafar (2004). Suppose b , the proportion of the total lead time used to manufacture the generic component, is known. For a given base stock level of generic component, the expected inventory level is given by:

$$I_0(S_0, b) = S_0 - \left(\frac{\rho_1(1-\rho_1^{S_0})}{1-\rho_1} \right), \quad (9)$$

where $\rho_1 = b\Lambda / \mu$.

The probability that the order-fulfilment time exceeds a quoted lead time w ($w \geq 0$) is given by

$$\Pr(T(S_0) \geq w) \approx \begin{cases} (1 + \rho^{S_0}(1-\rho)\mu w)e^{-\mu(1-\rho)w} & \text{if } \rho_1 = \rho_2 = \rho, \\ e^{-\mu_2(1-\rho_2)w} + \left(\frac{(1-\rho_2)\rho_1^{S_0+1}}{\rho_2 - \rho_1} \right) \cdot (e^{-\mu_2(1-\rho_2)w} - e^{-\mu_1(1-\rho_1)w}) & \text{otherwise} \end{cases} \quad (10)$$

For the CM configuration:

We have a special case of the MTS configuration with zero base stock levels. For this special case, the expected inventory level is zero and the promised lead time is given by:

$$w = \frac{\ln(1/\beta)}{\mu - \Lambda}. \quad (11)$$

3.4 The integrated Model

The relative merits of the three configurations will be compared based on the optimal profit within each configuration. The use of a profit rather than cost function is indeed an important differentiating factor between the proposed integrated approach and the traditional approach focusing on production-inventory systems. In the following discussion, we first present a

formal expression of the optimisation problem for each configuration. Subsequently, we present the solution procedures for determining the optimal solution for each configuration.

The MTS configuration

Define $\mathbf{x}=[x_1 x_2 \dots x_N]$ as a vector of product characteristics and $\mathbf{S}=[S_1 S_2 \dots S_N]$ as a vector of base stock levels. We formalise the manufacturer's optimisation problem as follows.

Problem P^{MTS}

$$\text{Max } Z(N, \mathbf{x}, \mathbf{S}, p) = \sum_{i=1}^N (p - c_{MTS}) \cdot \lambda_i(x_i, S_i, p) - h \cdot I_i(S_i) - K \cdot N \quad (12)$$

Recall that the optimal product line has a structure in which the market should be partitioned in segments of equal lengths. This means for a given N , $\pi_1 = \pi_2 = \dots = \pi_N$ and so $\lambda_1 = \lambda_2 = \dots = \lambda_N$. Because of this symmetry it is reasonable to have identical optimal base stock levels for all products i.e. $S_1^* = S_2^* = \dots = S_N^*$. As already discussed in § 3.2, for a given N we are able to determine the optimal \mathbf{x} using (2) and this optimal \mathbf{x} will not be affected by decisions made for the base stock level \mathbf{S} and price p . We also know that when the base stock level is given, we are able to calculate the promised lead time which in turn allows us to determine the optimal price using (4). This leads us to developing a two-stage based solution procedure. In the first stage we fix N and optimize \mathbf{S} , and in the second stage we optimize N .

From (7) it can be shown that the promised lead time w is linearly decreasing with S before reaching a zero level. It can also be proven that $I_i(S_i)$ is increasing and a convex function of S_i . This means that the expected total profit Z is a concave function of S , which eases us to determine the optimal base stock level. We now are able to determine the optimal solution for a given N . The next step is to optimise N which can be done by gradually increasing N starting from $N = 1$. For each value of N we optimise \mathbf{x} , p , and \mathbf{S} . The search can be terminated when the following condition is met: $(\bar{r} - c_{MTS}) \Lambda \leq K \cdot N$ is met. The left term in this condition is a constant and represents the maximum profit which can be gained by setting the price equal to the reservation price. The right term represents the proliferation cost which is linearly increasing with N . So the condition ensures that no better improvement is possible by increasing N .

The DD configuration

Problem P^{DD}

$$Z[b, N, \mathbf{x}, S_0, p] = \sum_{i=1}^N (p - c_{DD}) \cdot \lambda_i[x_i, S_0, p] - h_0(b) \cdot I_0[S_0, b] - K \cdot N \quad (11)$$

The optimal solution for the above defined problem can be obtained using a technique similar to the one used in solving the problem for MTS. For a given N we need to optimize \mathbf{S} and b , and then we need to optimize N . Different from the problem P^{MTS}, however, it is not easy to prove whether or not the profit function is concave in S_0 . Given that b is fixed, we know that $I_0(S_0)$ is increasing in S_0 and that when S_0 is relatively large we will reach a situation in which $w(S_0) \approx w(S_0 + 1)$. If we reach such a situation, no improvements can be made by increasing S_0 further. To optimize b , we use a simple search technique previously demonstrated in Wong et al. (2009). That is, we search over b values in the range $0 < b < 1$ using a pre-specified incremental factor. For example, if the incremental factor used is .1 then we start with $b=.1$ and end with $b=.9$. Then the next step is to optimise N which can be done using the same technique as for solving the problem P^{MTS}.

The CM configuration

As explained earlier, the manufacturer employing CM does not need to decide the number of products as they are capable to meet exactly the unique requirement of each individual customer. This means that N and \mathbf{x} are not relevant decision variables. In addition, no decision needs to be made for the base stock level \mathbf{S} since we have a MTO system i.e. $\mathbf{S} = \mathbf{0}$. Hence, price is the only relevant decision variable. The optimization problem for CM can be formulated as:

Problem P^{CM}:

$$\text{Max } Z[p] = (p - c_{CM}) \cdot \Lambda \quad (12)$$

Solving the problem P^{CM} is very straightforward since we just need to find the maximum price value that does not give a negative utility for customers. From (3) and (11), the optimal price can be determined as follows:

$$p_{CM}^* = \bar{r} - c_w w = r - c_w \frac{\ln(1/\beta)}{\mu - \Lambda} \quad (13)$$

4. Numerical Experiment

4.1 Parameter setting

In this section we present and discuss our numerical findings. Our main inquiry will focus on how different system parameters may influence the relative performance of each of the three configurations. Our experiment involves extensive data sets with a total of 5125 problem instances being tested. Table 2 presents all the parameter values used in the experiment. We fix the aggregate demand rate ($\Lambda = 5$) in this experiment. The reservation price is also fixed at $\bar{r} = 500$, which we consider large enough so that the net utility is always greater than zero, and so all customers will buy a product. Five different values of μ are used for the production rate. To study how the system's behaviour is affected by the sensitivity of customers to the delivery lead time and the deviation between their ideal preference and what are offered, different values of c_w and c_x are tested in this experiment. Further, five values are used as the product proliferation cost for the MTS and DD configurations. We fix the unit production cost for MTS and DD at $c_{MTS} = c_{DD} = 100$. We assume that these two costs are identical, so that at the very least this gives us an upper bound on the benefits of postponement. However, we test different values for the unit production cost of CM. Five values are used starting from $c_{CM}=100$, the same value as for MTS and DD. By setting the same unit cost for the three systems, we obtain a more optimistic setting for CM and may be able to gain some insights on how the CM performs by excluding the cost factor, i.e. by putting more focus on the trade-off between the lead-time and product variety. However, the larger values are also used to capture the inevitable fact that the unit production cost of CM is indeed higher due to investment in the new technology and more expensive materials, etc.

The parameter values used in this experiment are selected such that we are able to obtain general insights from the experiment rather than to represent any specific industrial case. As the sensitivity of the system performance (profit function) to one input parameter can be different from other parameters, some preliminary experiments were conducted to find a more reasonable range of values for different parameters. Our primary consideration is to set the parameter values in such a way that we are able to observe the optimality of each configuration.

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4.2 Numerical results

For each of the problem instances we apply the solution procedures presented in § 3 to determine the optimal decisions for the three configurations. This leads to the comparison of the three configurations being made on the basis of their maximum expected profits. A number of important findings are discussed in the following.

Comparing the overall performance

Figure 3 shows the overall average profit for each of the three configurations as a function of c_{CM} , the Custom Manufacturing unit production cost. As there is no effect of c_{CM} for MTS and DD, the average profits for these two configurations are constant. From the figure we can see that the overall performance of DD outperforms both MTS and CM and moreover, MTS outperforms CM. This observation represents the advantage of employing delayed product differentiation in compromising what can be offered by the other two configurations. MTS does not offer too many product variants but offers relatively short lead times while, in contrast, CM offers unlimited product variants but with the cost of longer lead times.

Figure 3 should be placed around here

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2 The above observation, however, does not reveal if there are any circumstances where CM
3 represents the best configuration. By examining more closely the individual data sets, we
4 found some cases in which CM indeed gains the largest profits. The results are summarised in
5 Figure 4. The figure shows that when the CM unit production cost is the same as the other
6 two configurations, there are 405 problem instances (out of 2500) in which CM gives the
7 largest profits. We still find 378 problem instances in which CM is the best configuration
8 when its unit production cost is slightly higher ($c_{CM}=105$). This observation suggests that the
9 relatively high production cost associated to the new technology could be one of the main
10 inhibitors for CM to become viable. Another interesting observation is shown in Figure 4a
11 where we plot those 405+378 instances as a function of the waiting time cost. It is clearly
12 shown that CM is only viable when the waiting cost is pretty low ($c_w=15$), which is the
13 minimum value used in the experiment. This means that the sensitivity of customers to the
14 waiting time seems to be an important factor too. These observations are only visible when
15 the proposed integrated approach is used. Traditional analyses focusing only on the
16 production-inventory system would lead to different and partial results.
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38 *Comparing the optimal number of product lines*

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40 Figure 5 shows the average of the optimal number of product lines for the different values of
41 the transportation cost for both the MTS and DD configurations. Recall that the number of
42 product lines is not relevant for CM and that the transportation cost represents customers'
43 dissatisfaction in not getting their ideal preferences. It is clear that increasing the
44 transportation cost would lead to more product lines. The figure also shows how the DD
45 configuration employing postponement has the advantage over the MTS configuration in
46 terms of number of product lines. This is inline with the well-known result of most studies
47 suggesting that postponement is an effective means in dealing with increasing product
48 proliferation. By holding the common intermediate good and executing the final
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customisation later, the DD configuration is able to minimise the customers' transportation cost by offering more product variants in the market than the MTS configuration. The proven success of Dell suggests that to a certain extent, PC customers seem to have good appreciation to the customisation feature introduced, reflecting a high transportation cost. But there are also applications in mass customisation e.g. customised shoes (Berger 2003) where we conjecture that these customised products serve only a niche market and the total market is still dominated by the mainstream products. It is not well understood whether the difference in the adoption level of the mass customisation concept is due to the difference in the transportation cost. Empirical research that attempts to assess and compare the transportation cost for different products would certainly be worthwhile.

Figure 5 should be placed around here

The effect of the production rate

Figures 6 and 7 show how the average profits for the three configurations are affected by the production rate. In Figure 6 the average profits for CM are obtained by including all the CM production costs from 100 to 125, while in Figure 7 only instances with $c_{CM}=100$ are included. Both figures indicate that increasing the production rate will improve the profitability of CM significantly. In Figure 6 we see that the average profit of CM is as high as the profit of MTS when the production rate is high and in Figure 7 is comparable to DD. The increase in the production rate has a more profound impact for the CM profitability relative to the other two configurations. This confirms our optimistic view that the advent of advanced manufacturing technologies facilitating shorter design and manufacturing lead times would certainly enhance the viability of CM.

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20 *Comparing CM with DD*

21 Figure 8 shows the average profit gain of CM over DD as a function of the transportation and
22 waiting costs. It is shown that the average profit for DD is higher in most of the cases. Only in
23 few cases when the waiting cost is low – customers are not sensitive to the waiting time, and
24 when the transportation cost is high – customers are really looking for products that meet their
25 individual requirement, employing CM deems to be more profitable. Further work to
26 empirically identify the range of products for which customers' preferences resemble the
27 above characteristic would certainly warrant attention.
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46 **6. Conclusions and directions for further research**

47 This paper is an attempt to extend the evaluation framework for assessing the value of
48 enhanced customisation. In contrast to the vast majority of existing studies where the focus
49 has been heavily on the production-inventory system, the model we developed tries to address
50 the important alignment between the production-inventory and marketing functions. Under
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2 this integrated perspective, we are able to get a more complete view on how factors including
3 inventory, lead time, price, and product variation are all important and hence, must be taken
4 into account when analysing customisation strategies.
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7 In this paper we compare three manufacturing configurations, each with a different
8 customisation level. The first configuration represents a traditional mass production setting
9 characterised by a make-to-stock mode. The second configuration represents a mass
10 customisation setting exploiting the benefit of postponement. And the final configuration
11 represents a pure customisation setting characterised by a make-to-order mode and facilitated
12 by advanced manufacturing technologies. The three configurations analysed correspond to the
13 movement that attempts to bring the Mass Customisation concept towards a state with a
14 greater degree of personalised offerings. We develop a stylised model that captures a number
15 of aspects pertinent in Mass Customisation, which can be associated to the production-
16 inventory as well as marketing decisions. For each of the three configurations we formulate
17 an integrated optimisation problem and devise a solution procedure to determine the optimal
18 set of decisions. This enables us to evaluate the relative merits of all the manufacturing
19 configurations based on their respective best performances.
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23 The results of our numerical experiment show how different system parameters may have an
24 impact on the preference of a certain manufacturing configuration. While our results are in
25 favour of most studies suggesting postponement as an effective means to accommodate mass
26 customisation, the proposed integrated approach allows us to examine the value of
27 postponement beyond the traditional inventory cost savings. The use of a profit instead of cost
28 function offers a more complete and holistic understanding of postponement benefits as the
29 model captures the postponement capability in compromising product variety and delivery
30 lead time on top of cost savings gained from reduced inventories.
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34 Our numerical study provides some insights on some important aspects that may inhibit as
35 well as potentially facilitate the movement towards a highly customised manufacturing. The
36 main inhibitors include the high unit production cost associated with the investment in new
37 manufacturing technologies and the customers' sensitivity to the order waiting time. In the
38 case of Rapid Manufacturing technologies, for example, the production cost remains as one of
39 the major constraints due to the high machine as well as material prices. We may need to
40 wait for a few years to reach a state where products would become more affordable, which
41 will then able to grow a niche market into a more mass market of custom manufactured
42 products. With regard to the second inhibitor, however, the developments have been more
43 promising. There are no doubts that those technologies are capable of reducing the total
44 design plus manufacturing lead time considerably. Even though it is not possible to achieve
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2 the same order waiting time as in the mass production environment supported by finished
3 goods inventory, this capability would certainly enhance the viability of Custom
4 Manufacturing particularly in markets where customers' order waiting time should not be
5 prohibitively long.
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9 As in all models, our model has limitations. First, our results rely on the assumption that
10 customers are identical in terms of their reservation price, transportation cost, and waiting
11 cost. In the situations where customer heterogeneity is more evident, some key insights may
12 change. For example, if consumers are allowed to have uncommon reservation price for their
13 ideal products, the full market coverage may no longer be optimal. To address this limitation,
14 the market demand model can be extended by, for example, allowing consumers to have
15 uncommon reservation price for their ideal products. One scenario that would be worthwhile
16 to examine is to capture the possibility that customers are willing to pay more for a greater
17 degree of customisation, and therefore have an impact on the assessment. The second
18 limitation is due to the fact that the model ignores competition. Extending the model by
19 incorporating competition where products manufactured by the three different configurations
20 may co-exist in the market may prove to be useful. Such a study will complement the existing
21 models analysing competition between firms adopting mass production and mass
22 customisation strategies. Furthermore, empirical research to assess different parameters in
23 real settings is a challenge. In particular, research to estimate the customers' disutility
24 associated with lead time as well as to the deviation between their ideal taste and what is
25 offered would be very valuable. This research will not only useful in placing the performance
26 comparison in a more realistic scale, but also in acquiring enhanced explanation of why some
27 mass customisation practices are successful while some others not.
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Appendix

Recall that the optimal price that covering a complete market is equal to

$$p_0 = r - c_w w - \frac{c_x}{2N}. \quad (\text{A.1})$$

Increasing the price will obviously result in reduced market coverage. It is easy to see that a price increase of Δp ($0 \leq \Delta p$) will reduce the market coverage by $\frac{\Delta p}{c_x}$. The revenue function

as a result of a price increase of Δp can be represented as:

$$R = \Lambda \left(1 - 2 \frac{\Delta p}{c_x} N\right) (p_0 + \Delta p) = \Lambda p_0 + \Lambda \Delta p - \frac{2\Lambda \Delta p N p_0}{c_x} - \frac{2\Lambda N (\Delta p)^2}{c_x} \quad (\text{A.2})$$

Differentiating R with respect to Δp , the first order condition for maximising this function is

$$\frac{dR}{d \Delta p} = \Lambda - \frac{2\Lambda N p_0}{c_x} - \frac{4\Lambda N \Delta p}{c_x} = 0. \quad (\text{A.3})$$

Solving for Δp we obtain the optimal price increase:

$$\Delta p^* = \frac{c_x}{4N} - \frac{p_0}{2} \quad (\text{A.4})$$

The second-order condition is given by

$$\frac{d^2 R}{d \Delta p^2} = -\frac{4\Lambda N}{c_x} < 0, \quad (\text{A.5})$$

which fulfils the requirement for a local maximum of the total revenue.

From (A.1) and (A.4), we can now determine the optimal price from

$$p^* = \begin{cases} r - c_w w - \frac{c_x}{2N} & \text{if } r - c_w w \geq \frac{c_x}{N}, \text{ or} \\ \frac{r - c_w w}{2} & \text{if } r - c_w w < \frac{c_x}{N}. \end{cases}$$

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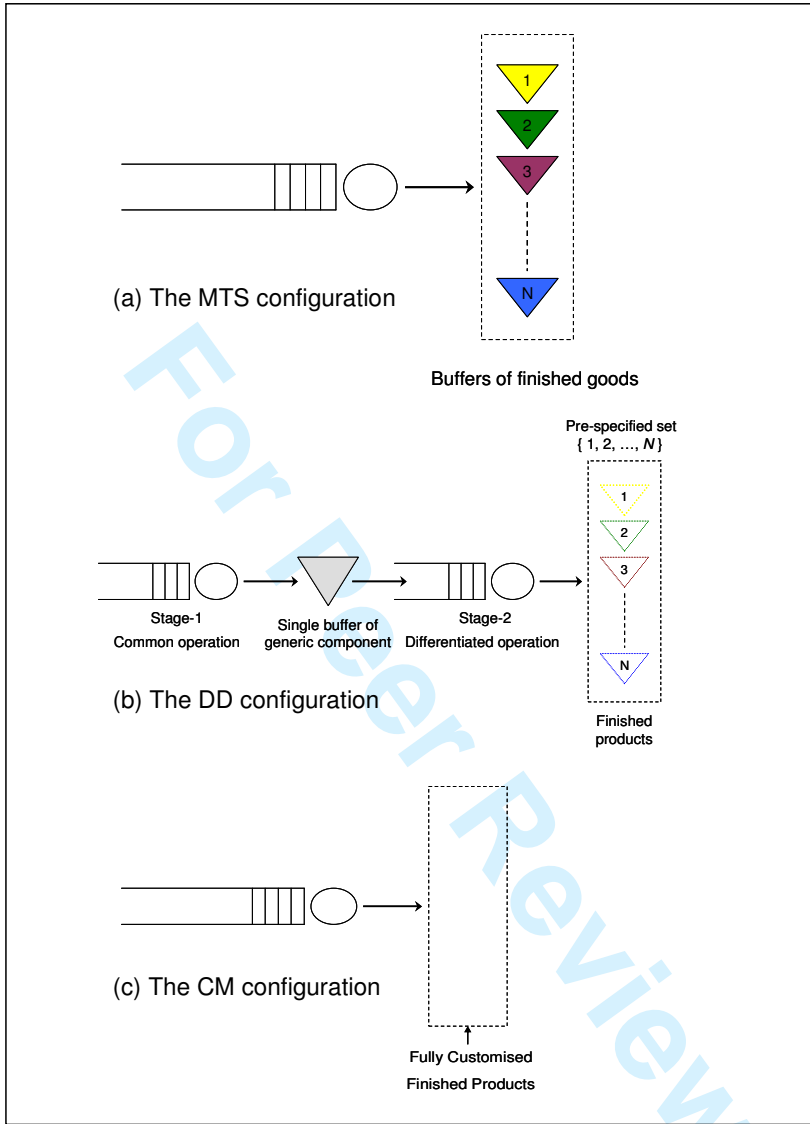


Figure 1. Description of the three configurations

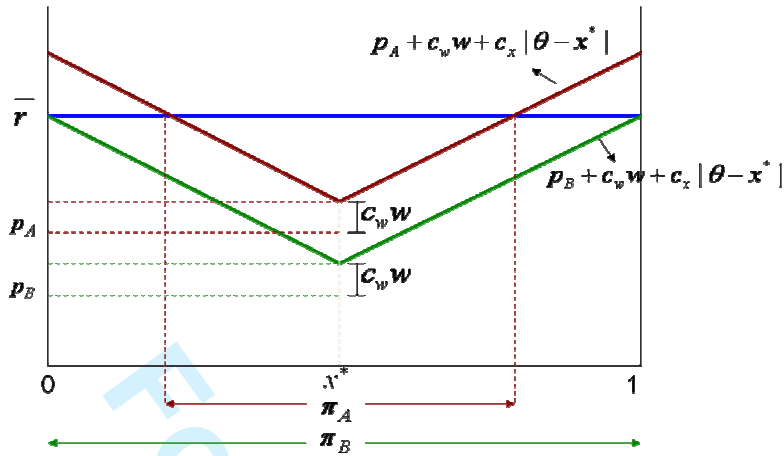


Figure 2. Complete vs. partial market coverage

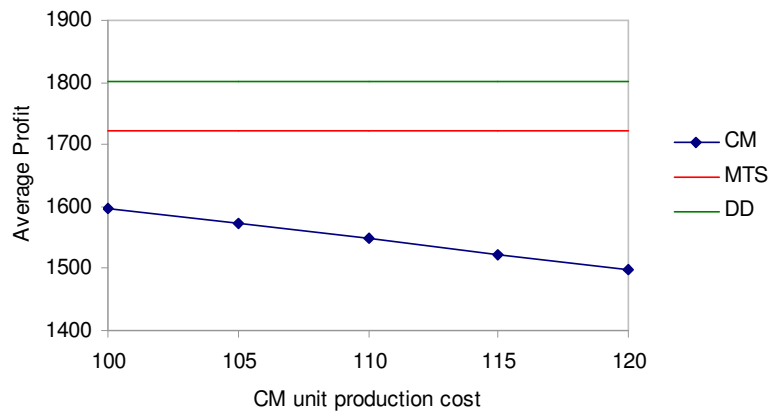


Figure 3. The overall profit comparison

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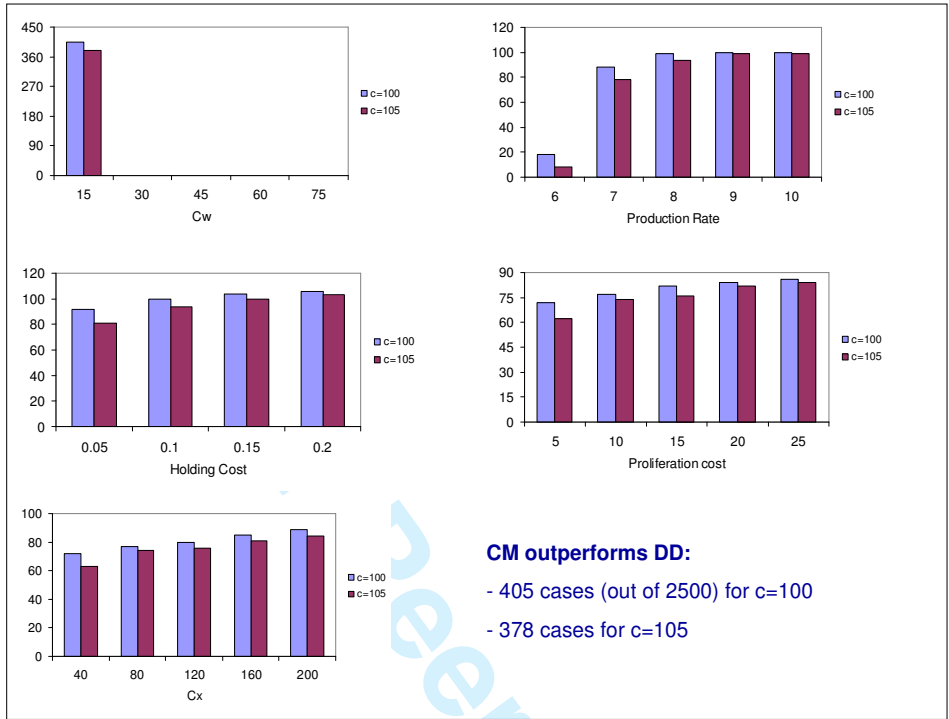


Figure 4. The special cases in which CM has the largest profits

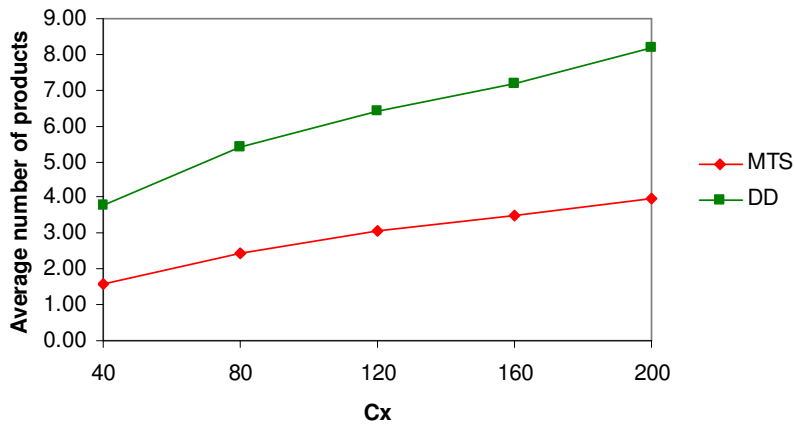


Figure 5. Comparison of the optimal number of product lines for MTS and DD

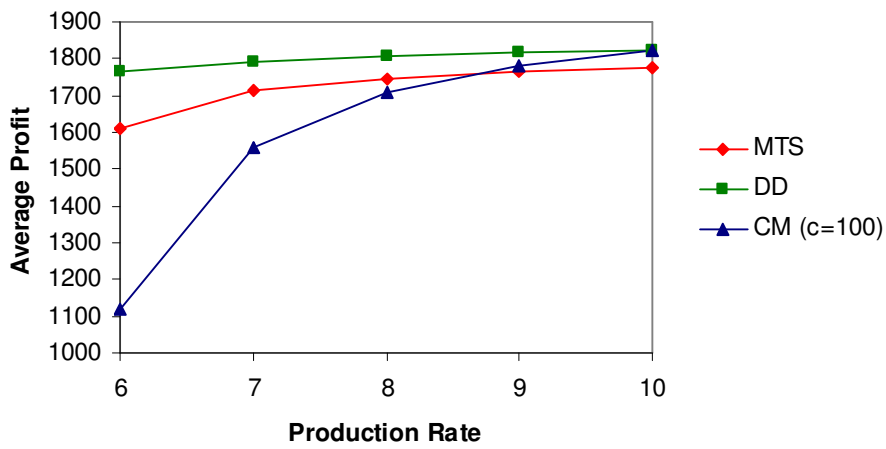


Figure 6. The effect of production rate to the total profits (all c_{CM} are considered)

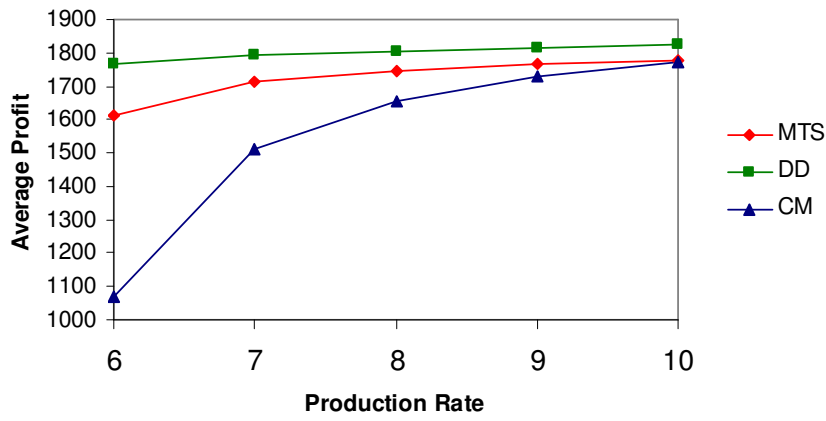


Figure 7. The effect of production rate to the total profits (only $c_{CM}=100$ is considered)

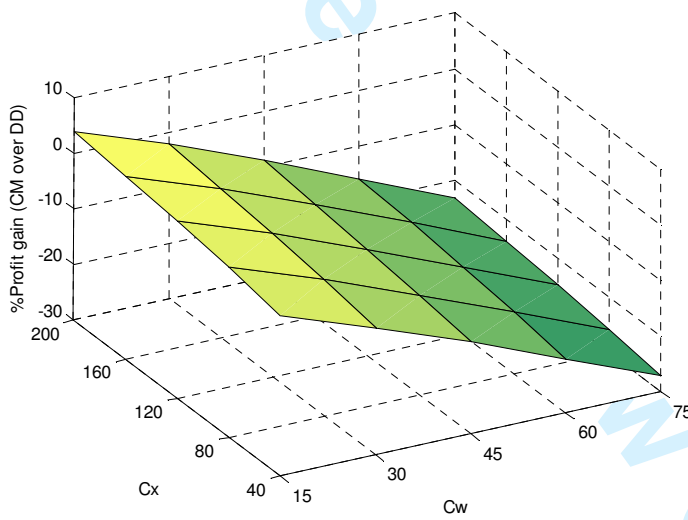


Figure 8. Profit comparison between DD and CM

Table 1. List of Notation

<u>Demand input parameters</u>	
Λ	Total potential demand rate
π_i	First choice probability of product i
λ_i	Demand rate for product i
\bar{r}	Customer reservation price
$1-\beta$	Service level – probability that delivery will occur within a promised lead time
<u>Production input parameters</u>	
μ	The production rate for the MTS configuration
μ_1	The production rate at Stage-1 for the DD configuration
μ_2	The production rate at Stage-2 for the DD configuration
b	The fraction of the total lead time required to make the generic component
μ'	The production rate for the CM configuration
<u>Cost parameters</u>	
h	Unit inventory holding cost for the finished product
h_0	Unit inventory holding cost for the generic component
c_{MTS}	Unit production cost for the MTS configuration
c_{DD}	Unit production cost for the DD configuration
c_{CM}	Unit production cost for the CM configuration
K	Product proliferation cost for the MTS and DD configuration
c_x	Linear transportation cost (deviation from the ideal preference)
c_w	Linear delay or waiting cost
<u>Decision variables</u>	
S_i	Base stock level for the finished products
S_0	Base stock level for the generic component
\mathbf{S}	Vector of base stock levels
N	Number of product lines
x_i	Product i 's characteristic
\mathbf{x}	Vector of product characteristics
p	Product price
w	Promised delivery lead time (determined by inventory policy)
<u>Performance measures</u>	
I_i	Expected on-hand inventory level for the finished products
I_0	Expected on-hand inventory level for the generic component
Z	Expected total profit

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Table 2. The parameter values used in the numerical experiment

Parameter	Unit	Number of values	Values
Λ	/ time unit	1	5
\bar{r}		1	500
$c_{M\text{TS}}, c_{D\text{D}}$	£	1	100
$c_{C\text{M}}$	£	5	100, 105, 110, 115, 120
μ	/ time unit	5	6, 7, 8, 9, 10
h_i	£/unit/time unit	4	5, 10, 15, 20
c_w	£	5	15, 30, 45, 60, 75
c_x	£	5	40, 80, 120, 160, 200
K (for MTS and DD)	£	5	5, 10, 15, 20, 25

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