Competitive Due-Date Setting Management Across Marketing and Manufacturing

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Abstract

This research investigates the problem of due-date coordination and negotiation between the marketing and manufacturing entities within a make-to-order firm. Marketing is concerned about satisfying customers who each have a preferred due-date for their orders but are willing to compromise in return for price discounts. Manufacturing is concerned about the efficient utilization of capacity and is not willing to offer any given order a higher service levels unless the incurred cost is reimbursed. The reimbursement also rewards manufacturing for risk sharing with marketing. Operating in an environment of dynamic order arrivals, we design a Nash game between marketing and manufacturing. Each party quotes a due-date based on its utility function defined by local cost structure, a belief function of job completion times, and an agreed penalty when the quoted due-date is missed. We identify properties for each agent's utility function under which a unique Nash equilibrium exists. We observe that due to double marginalization the solution (due-date quotation) achieved at Nash equilibrium is never the system optimum. In order to bridge the gap between the competitive and global optimization of the system, we derive transfer payments between marketing and manufacturing with which the system optimal solution can be achieved at Nash equilibrium. We conduct sensitivity analysis on the transfer payments such that they could be tailored for alternative utilities.

1. Introduction

Filling customer orders in a timely manner has become one of the most prominent theme in recent years for make-to-order companies in a growing global and competitive market. The escalating pressure for competent and improved customer service has fettered make-to-order manufacturers to investigate ways to satisfy customer demand quickly at a lower cost [1]. In contrast with the most of the literature on due-date scheduling where the due-dates are assumed to be exogenous, in most real life situations, the determination of the due-dates is negotiable and generally, is the responsibility of the marketing department of the firm. When setting the due-dates, besides the customer preferences, the firm is also constrained with the shop floor capabilities such as capacity utilization. The capacity utilization, which is managed by the manufacturing department, is the most important factor that determines the manufacturing flow times. In order for the firm to maintain a cost-effective service for customers due-date quotation and capacity utilization decisions should be coordinated. The due-date setting decision integrated with the shop floor status has been studied recently in various contexts [2-7] in which the problems are studied under centralized systems. Central models assume that the departments within the company cooperates and do not deviate from the global optimal solution. However, due to the fact that employees are rewarded based on their departments' performance, each department has incentives to behave according to their own local cost structure in most cases. Thus, each department incurs only a portion of the system cost so that the system optimal solution may not minimize each department's cost. Consequently, coordinating the marketing and manufacturing departments becomes a challenging issue that must be handled using appropriate mechanisms [8]. In resent years, the coordination of operations has been mostly studied between independent agents within a supply chain [9-12] as well as between departments within a firm [13-15]. Among the former group of work, Grout [10] proposes a model of incentive contracts between a buyer and a supplier for timely delivery of orders. In his setting, the buyer dominates the supplier and moves first by selecting an incentive scheme composed of on-time delivery bonus and tardiness penalty for the supplier such that an optimum probability of on-time delivery is ensured by the supplier who responds to that scheme by selecting a flow time allowance that will minimize her expected cost. It is observed that achieving exactly 100% on-time delivery performance is not optimal and many times it is even unattainable. In the later group of work the coordination mechanisms designed between internal markets are, in general, based on departments efforts that effect demand and capacity outcomes and decisions in quantities and price.

In this paper, we propose incentive mechanisms for coordinating the marketing and manufacturing departments over due-date quotation decisions. We consider a make-to-order firm that operates in a decentralized fashion where marketing determines the due-date to be quoted for the outside customer who has a preferred delivery date for her order and manufacturing quotes its own due-date for the marketing whose preferred delivery date is the one quoted to the outside customer. The due-date quoted to marketing is the date where a preset service level is ensured. Hence change in the due-date implies a change in the capacity utilization. We define the service level as the cumulative probability that the order will not be tardy given the manufacturer's quoted due-date. The mentioned cumulative probability is calculated based on the believes regarding the completion time of the order which is formulated as the belief function and assumed to have the form of a Weibull probability distribution function. In real life applications generally it is very tedious to capture the accurate flow time probability distribution in which cases an approximation can be necessary. Employing Weibull distribution functions can be useful to carry out this task as one can generate various probabilistic density structures by modifying the shape parameter. Weibull distributions can take the shape of different distributions such as Normal, Lognormal, Gamma and several Pearson type distributions [16] so that they can be used to model a high variety of systems. Also, it should be noted that exponential and Raleigh distributions are special cases for Weibull distribution. For our case assuming Weibull distribution for the belief function also significantly facilitates our analysis. We assume that the belief function is identical for each department and all parties are completely informed with all parameters in the system.

The departments play a Nash game where the parties simultaneously choose their due-date quotations and once announced, the decisions cannot be modified. In our model, both marketing and manufacturing is penalized for quoted longer due-dates. The marketing department is charged for the discount in price incurred as a result of deviation between its quoted due-date and the customer's preferred delivery date. The manufacturing charges the marketing with a constant price for processing the order, however, issues a discount based on deviation of its promised delivery date from the marketing's quoted due-date. Marketing is mainly responsible for the tardiness cost but manufacturing compensates this to a certain degree only if realized completion date of the order is later than the due-date quoted for the marketing by the manufacturing. As pointed out above, for the manufacturing, promising earlier delivery dates means an increase in the capacity and the incurred cost is charged to the department. In such a game each department minimizes its own cost given the behavior of the other department, and therefore neither department has an incentive to deviate from the equilibrium of the game.

In our analysis, we observe that for some nonrestrictive parameter settings there is always a unique Nash equilibrium for the game. Comparison of the game's equilibrium to the system optimal solution reveals the fact that the system optimal solution is never a Nash equilibrium except for very special cases. Hence, the competitive decision making reduces the efficiency and a need for a cooperative solution arises. To achieve that, we propose a set of contracts that eliminates the incentives for the departments to deviate from the optimal solution. These contracts specify transfer payments between departments that are formed based on the cost entities within the system. We also conduct sensitivity analysis on the transfer payments such that they could be tailored for alternative local cost structures.

The next section elaborates the description of our model and related assumptions. In Section 3, we present the central model. The details of the decentralized model the analysis of equilibria are described in Section 4. Section 5 discusses the contracts that achieve the coordination between the departments, and Section 6 concludes.

2. Model Description

We consider a make-to-order firm that serves due-date sensitive customers. The marketing department of the firm is concerned about satisfying customers who each have a preferred due-date for their orders but are willing to compromise in return for price discounts. On the other hand, the manufacturing department is concerned about the efficient utilization of capacity and is not willing to offer any given order a higher service level unless the necessary cost to accomplish this is reimbursed. In this section we formulate a model that can be used to analyze the competitive due date and capacity management across these departments. In our setting, the marketing department receives orders attached with preferred delivery dates which we will refer to as *customer preferred due dates* (cd_i) for job i throughout the rest of this paper. Based on the feedback from the manufacturing department, the marketing agent may quote a later due date in return for a certain amount of discount to the customer in the price of the job which is assumed constant. We call this quoted due date as *negotiated due date* (dd_i). As obvious, if the due date received from the customer is the due date also quoted by the marketing manager, the negotiated due date will be equal to the customer due date. We assume that the negotiated due date can not be less than the customer due date since there is no incentive, such as consideration of earliness penalty, for the firm to do so. On the other hand, there is a certain penalty for tardiness which is linear in the amount of lateness when it is positive. We do not consider the option of rejecting an order. Also we assume that the customers will accept the quoted due dates as long as a discount proportional to the difference between dd_i and cd_i is offered by the marketing.

In our setting, none of the department managers are expected to have control over the entire firm and therefore can not optimize it alone. Instead, each department will try to optimize his or her own utility being aware that the other department will do the same thing. The decisions of both marketing and manufacturing divisions highly depend on the belief function regarding the completion date of the order which is shaped by three types of input. These are namely, the information procured from the orders that are already waiting in the system, the expectations regarding future arrivals of other orders and the capacity utilization. The first type of input may include the due dates quoted for formerly arrived orders (confirmed orders), their processing times and capacity allocated to them by the manufacturing department. The unknown future customer orders (prognosed orders) should be taken into consideration so as to give more accurate decisions that hinge against the uncertainties so that expected loss of future opportunities can be minimized. Clearly, the service level rendered by the manufacturing department for an order becomes an other important influence on the belief on the completion time of that order. As the service level increases the probability of earlier completion time increases. It is assumed that the belief function has the form of a continuos probability distribution function and mutually shared by two parts.

Since the manufacturing department is the responsible unit for the processing of the orders, it can be looked as a supplier working for a specific retailer in a competitive supply chain environment. Basically, it sells capacity, which comes with a cost, for the orders issued by the marketing department. In our model, the capacity utilization is represented by the *promised completion time (pc_i)* quoted for the marketing by the manufacturing department, which can be defined as the time where a certain prescribed service level is first attained. In our study we define the service level, θ $(0 < \theta < 1)$, at pc_i as the probability that the job will be completed on or before pc_i. We assume that this service level is predetermined and fixed so that it is a given parameter. In the model pc_i will be employed as the decision variable for the manufacturing department and will effect the belief function for the order completion time. Obviously as pc_i decreases the capacity utilization increases so that θ can be attained at this new point. Therefore the change in pc_i means a change in the capacity utilization and thus, it represents the capacity related decision of the manufacturing department. We consider capacity utilization changes for a relatively short term such as running overtime, hiring part-time or temporary workers, arrangements in lot sizes and schedules, altering process plans, short term changes in order release procedures, expediting shipments etc. In fact, pc_i can also be regarded as the due date quoted for the marketing by the manufacturing. In this setting, the marketing makes a constant payment to the manufacturing for processing the job. However, a certain amount of this payment is returned by the manufacturing that is proportional to the difference between pc_i and dd_i. As a result it can be clearly observed that the relationships between the outside customer and the marketing and, between the marketing and the manufacturing are similar where one side announces a preferred due date and the other quotes a due date as a response to that.

On the arrival of a new order the following sequence of events takes place: (1) outside customer places her order with a due-date; (2) simultaneously, the marketing and manufacturing announce the negotiated due date and the promised completion time; (3) the price of the job less the discount proportional to the difference between the negotiated due date and the customer due date is charged to the outside customer and, the marketing is charged by the manufacturing according to the price of processing the job less the discount proportional to the difference between the promised completion time and the preferred due date of the marketing which is the negotiated due date; (4) production occurs and the job is completed; (5) tardiness costs are charged.

Let $\bar{c}_i$ be the realized completion time of order i and, ϕ and Φ be the Weibull density and distribution functions regarding the belief of the completion time. Both ϕ and Φ are also functions of pc_i. We assume $\Phi(x, pc_i)$ is continuous when $pc_i \geq 0$, 0 when $pc_i < 0$, increasing in x and decreasing in pc_i, and differential for both $x \geq 0$ and $pc_i \geq 0$. As underlined above capacity is a function of pc_i (vice versa) where as pc_i decreases capacity utilization increases and as capacity increases the value of the cumulative distribution function increases for any $x\,(0 < x < \infty)$. Moreover, $\Phi(0, *) = 0$, so that completion times are positive and $\Phi(pc_i, pc_i) = \theta$ for all $pc_i > 0$. In general, we consider any continuous density function assuring that the expected tardiness, and thus the expected completion time, up-slopping with pc_i in convex fashion. Let λ be the inverse of the scale parameter at the beginning for the belief function and z the fractional increase in λ's value representing the increase in capacity utilization. Consequently, after the increment the resulting scale parameter will be $1/(\lambda(1+z))$ and assuming Weibull distribution

$$\lambda(1+z)=\frac{(-ln(1-\theta))^{1/\alpha}}{pc_i} \tag{1}$$

where α is the shape parameter for the density function.

Figure 1 can be employed to illustrate the events explained above. Before players give any decision the customer orders are received and the present shop floor conditions are realized at the first stage. Hence customer preferred due date, cd_i, and the current θ-service-level date, pc_o $(pc_o = (-ln(1-\theta))^{1/\alpha}/\lambda)$, are established prior to the game (Figure 1.a.). In the next stage, players announce their decisions simultaneously. The customer due date is negotiated to dd_i and the new θ-service-level date is moved to pc_i as a result of change in the belief function that is due to the capacity adjustment at the manufacturing department. Let $A = (0, dd_i]$, $B = (dd_i, pc_i]$ and $C = (pc_i, \infty)$ (Figure 1.b.).

If $\bar{c}_i \in A$ then the customer's shipment will not be late and thus no tardiness penalty occurs unless $\bar{c}_i \in C$ and $dd_i \geq pc_i$ in which case the manufacturing is penalized by the marketing for being tardy. We consider the possibility for the marketing's negotiated due date being greater than the manufacturing's promised completion time in our analysis both for global and competitive optimization. As will be elaborated in the next section, the position of pc_i with respect to dd_i will make but direct impact on the global optimization since for the center only the resulting capacity adjustment will be meaningful and as long as global optimum resides in a region where $pc_i^o \leq dd_i^o$ there will be no incentive for the center for not to steer her decisions towards this region. In the competitive game the manufacturing (marketing) manager may have incentives to take his (her) decision below (above) marketing's (manufacturing's). This only happens when cd_i is less than pc_o or very close to it. We assume that the deviation penalty will still be charged when $dd_i \geq pc_i$. This assumption is needed to make our analysis more tractable and can be justified by the implicit inclusion of holding or precipitated shipment as a result of too early completion. It can be presumed that this cost is negligible in general so that it is not included in our models but becomes notable as the service level at dd_i exceeds θ which is unwanted and thus, the marketing imposes incentives for the manufacturing for preventing this happens as much as possible through charging him with the mentioned deviation cost.

When $\bar{c}_i \in B$, the order is tardy for the customer and the marketing pay all the tardiness penalty. Manufacturing is not charged since the order is completed on or before pc_i. Note that if $dd_i \geq pc_i$ then $B = \{\emptyset\}$. While $dd_i \leq pc_i$, $\bar{c}_i \in C$ means that the manufacturing shares the tardiness penalty with the marketing proportional to the difference between $\bar{c}_i$ and pc_i that is adjusted by γ.

We assume that there is no cost for placing and processing an order. The due date delay costs which reflect discounts both from marketing to the outside customer and from manufacturing to marketing increase quadratically with the difference between dd_i and cd_i, and pc_i and dd_i with cost coefficients g_i and n_i ($g_i > n_i$) respectively. The quadratic discount function implies that a customer becomes less willing for any additional deviation from her preferred due date with an increasing rate. Using such a function is significantly helpful in our analytical analysis because of its well behavior towards guaranteeing convexity and existence of equilibria. The marketing is charged tardiness penalty a_i ($a_i > g_i$) per unit of positive lateness from dd_i. This penalty may represent the proxies for loss of customer good will, supplementary shipping and handling costs due to the tardiness and/or the cost of the reimbursement. The manufacturing is charged γa_i per unit of tardiness from pc_i by the marketing where $0 \leq \gamma \leq 1$. This implies that if the job is competed after the manufacturing's promised time, the manufacturing shares the certain portion of the tardiness cost specified by γ which is exogenous. Let pc_o be the first time point at which θ service level is guaranteed at the first stage of events where new order arrival along with cd_i, has been observed just before the competing sides' actions. Thus, pc_o reveals the initial and/or regular capacity utilization level allocated to the new arrival. Finally, m_i ($m_i > n_i$) is the coefficient of the cost for improving θ-service-level from pc_o to pc_i which is also assumed to be increasing quadratically with their deviation from each other.

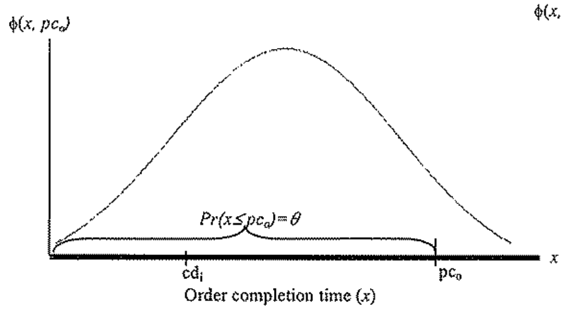

Figure 1.a. Initial stage and belief function before the actions of the marketing and manufacturing.

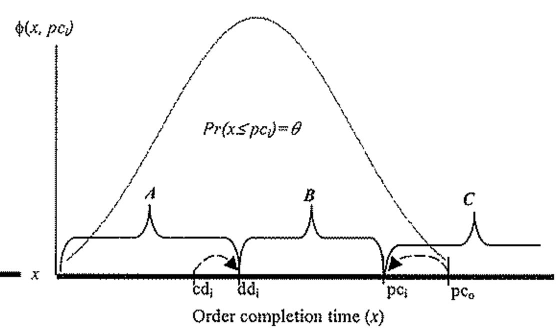

Figure 1.b. Belief function after parts act

In the following section we start our analytic analysis with elaborating the center's model that is aimed to minimize the total system cost. As for further notation, $[x]^+$ is used instead of $max(0, x)$ and $[x]^-$ instead of $min(0, x)$. $E[x]$ returns the expected value of random variable x and $\mu(pc_i)$ is the expected completion time of the order when the second argument in the density function is pc_i. $f^{(i)}(*, *)$ denotes the first derivative of f with respect to its ith argument.

3. Center's (System) Optimal Solution

In general, the problem of the center can be stated as minimizing the total cost of due date quotation and capacity utilization management incurred within the firm. There exists a substantial relationship between decisions regarding due date quotation and capacity utilization. Whilst the due dates quoted for customers hinges on the service level utilized in the manufacturing division of the firm, the capacity adjustments are carried out based on the competent service quality which is mainly shaped by the market requirements for being competitive. Basically, there are three cost components for the center in this model: 1) cost due to the discounts that are granted in order to convince the customer for a later due date, 2) tardiness cost and 3) capacity increment cost. Consequently, the expected cost function of the center can be given as follows;

$$G_o = g_i(dd_i - cd_i)^2 + m_i(pc_o - pc_i)^2 + a_i E[[\overline{c}_i - dd_i]^+]$$

where

$$E[[\overline{c}_i - dd_i]^+] \ = \int_{dd_i}^{\infty}(x - dd_i)\phi(x, pc_i)dx$$

It should be underlined that the penalty due to the deviation between dd_i and pc_i does not influence the center's model since it is but the transfer payment between the departments within the firm. Basically, this transfer is similar to the supplier's price of the product asked from the retailer in a supplier-retailer supply chain environment which is not involved in the supply chain's profit function. Finally, we can write down the model of the center as follows;

$$P(1) \qquad Min \quad G_o$$

s.t.

$$dd_i \geq cd_i$$

$$pc_i \leq pc_o$$

The first constraint ensures that the customer will not be quoted for a due date that is earlier than her preferred due date and second constraint implies that the capacity utilization cannot be reduced. Next we investigate the convexity of the center's cost function.

LEMMA 1. *Assuming ϕ is Weibull G_o is a strictly convex function*

PROOF. We first show that both dd_i ($dd_i \geq 0$) and pc_i ($pc_i \geq 0$) are convex in G_o.

$$\frac{\partial^2 G_o(dd_i, pc_i)}{\partial dd_i^2} = 2g_i + a_i\phi(dd_i, pc_i)$$

Since the density function is greater than or equal to zero and all cost coefficients are strictly positive G_o is strictly convex when $dd_i \geq 0$.

$$\frac{\partial^2 G_o(dd_i, pc_i)}{\partial pc_i^2} = 2m_i + a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx$$

Since expected tardiness is convex in pc_i and all cost coefficients are non zero positive numbers G_o is strictly convex when $pc_i \geq 0$. Thus, we showed that all 1st principal minors of the Hessian of G_o are strictly positive. The determinant of the Hessian can be written as follows;

$$2g_i\left(2m_i + a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx\right) + 2m_i a_i \phi(dd_i, pc_i)$$
$$+ a_i\phi(dd_i, pc_i) a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx - \left(a_i \Phi^{(2)}(dd_i, pc_i)\right)^2$$

It is clear that

$$2g_i\left(2m_i + a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx\right) + 2m_i a_i \phi(dd_i, pc_i) > 0$$

Hence if

$$a_i\phi(dd_i, pc_i) a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx - \left(a_i \Phi^{(2)}(dd_i, pc_i)\right)^2 \geq 0$$

(2)

the Hessian is positive definite meaning that G_o is strictly convex and this inequality is binding when ϕ is any Weibull density function.

□

For the next Lemma let dd_i^o and pc_i^o be the due date and the promised completion date values that minimize the unconstrained system cost function. Furthermore assume pc_o is a positive number large enough so that pc_i is always going to be greater than 0.

LEMMA 2. dd_i^o and pc_i^o minimize $P(1)$.

PROOF. Optimum value for dd_i^o as a function of pc_i can be found by computing the derivative of G_o with respect to dd_i after fixing pc_i and solving it for dd_i. The resulting equation will be as follows;

$$dd_i^o = cd_i + \frac{a_i}{2g_i}\Phi(dd_i^o, pc_i^o)$$

In same manner the equation that gives pc_i^o can be derived and written as follows;

$$pc_i^o = pc_o - \frac{a_i}{2m_i}\int_{dd_i^o}^{\infty}(x - dd_i)\phi^{(2)}(dd_i^o, pc_i^o)dx$$

Since we haven't specified a certain distribution function we can't generate the closed form values for these decision variables. Even if we assume a certain distribution function it still may not be possible to obtain closed form definitions. In this case a simple recursive search can be employed if not find to approximate these values in a very reasonable time given that G_o is strictly convex.

We know that $\Phi(dd_i^o, pc_i^o)$ is positive. Therefore, dd_i^o is always greater than cd_i for all $pc_i^o \geq 0$. In the second equation pc_i^o will always be positive as long as pc_o is a sufficiently large positive number. Also we know that the expected tardiness increases in pc_i which means that the derivative of the second component at the right hand sight of the equation is positive. Hence, $pc_i^o \geq pc_o$.

□

Consequently, we can drop the constraints from $P(1)$ and use the closed form function as the center's model. It is obvious that if $cd_i \geq pc_o$ then $dd_i \geq pc_i$. However, the statement is not true in the reverse direction unless $(pc_o - cd_i)$ is large enough. Now that we have introduced the center's model, we can start to investigate the game between the marketing and manufacturing couple.

4. Due Date Quotation and Capacity Utilization Game

In this game, the sides are considered as independent players. The game, Ω, consists of a single move where players simultaneously choose their strategies. The strategy space of the marketing, σ_1, is limited with a lower bound, cd_i, and has no upper bound. Hence, $dd_i \in \sigma_1 = [cd_i, M]$ where M is a very large arbitrary constant that will never constraint the marketing in her decision. The strategy space for manufacturing, σ_2, is bounded with 0 and pc_o, that is, $pc_i \in \sigma_2 = [0,\, pc_o]$. All sides have complete information regarding others' cost functions and thus, all parameters in the model are common knowledge. The belief functions over the completion time of the order identical across both players.

Let $H_j(dd_i, pc_i)$ denote the player j's expected cost when players employ the joint strategy of (dd_i, pc_i). In particular, j is equal to 1 for the marketing and 2 for the manufacturing. The best response mapping for player j is a set-valued function corresponding each strategy of player k $(k \neq j)$, with a subset of σ_j and formally defined as follows for each player in this game;

$$r_1(pc_i) = \left\{ dd_i \in \sigma_1 \mid H_1(dd_i, pc_i) = \min_{x \in \sigma_1} H_1(x, pc_i) \right\}$$

$$r_2(dd_i) = \left\{ pc_i \in \sigma_2 \mid H_2(dd_i, pc_i) = \min_{x \in \sigma_2} H_2(dd_i, x) \right\}$$

In this setting a pure strategy Nash equilibrium is a pair of quoted due date and θ-service-level date, (dd_i^N, pc_i^N), such that each player chooses a best reply to the other player's equilibrium decision. Namely,

$$dd_i^N \in r_1(pc_i^N)$$

$$pc_i^N \in r_2(dd_i^N)$$

In this study our focus is on examining the conditions under which a unique pure strategy equilibrium can be guaranteed. Therefore, we do not take any mixed strategy analysis into consideration.

4.1. Models of the Players

The marketing is charged for the deviation of negotiated due date from the customer preferred due date and the tardiness. If the manufacturing completes the order later than his promise he compensates the tardiness penalty that the marketing pays determined by γ parameter. Marketing also charges the manufacturing for the deviation between pc_i and dd_i. Following is the cost function of the marketing division;

$$H_1(dd_i, pc_i) = g_i(dd_i - cd_i)^2 + a_i \int_{dd_i}^{\infty}(x - dd_i)\phi(x, pc_i)dx - \gamma a_i \int_{pc_i}^{\infty}(x - pc_i)\phi(x, pc_i)dx - n_i(pc_i - dd_i)^2$$

where $cd_i < dd_i < M$.

LEMMA 3. *For any $pc_i \geq 0$, $H_1(dd_i, pc_i)$ is strictly convex in dd_i.*

PROOF. Fix pc_i and take the second derivative of $H_1(dd_i, pc_i)$ with respect to dd_i :

$$\frac{\partial^2 H_1(dd_i, pc_i)}{\partial dd_i^2} = 2g_i + a_i\phi(dd_i, pc_i) - 2n_i$$

since $g_i > n_i$ and $a_i\phi(dd_i, pc_i) \geq 0$ the second derivative will be strictly greater than 0. Therefore the foregoing function is strictly convex.

□

Due to the fact that the density function will be equal to 0 when $pc_i < 0$, we can go ahead one step and conclude that H_1 is strictly convex in general. Define dd_i^* as the only value that minimizes H_1 for a given pc_i. This value can be found using the equation $H_1^{(1)}(dd_i^*, pc_i) = 0$,

$$\mathrm{r}_i(pc_i) = dd_i^* = max(cd_i, \frac{2g_i cd_i - 2n_i pc_i + a_i(1 - \Phi(dd_i^*, pc_i))}{2(g_i - n_i)}) \quad (3)$$

The manufacturing is charged for the deviation of promised completion date from the negotiated due date and the tardiness with respect to the promised completion date. Manufacturing is also charged for capacity increase. Following is the cost function for the manufacturing division;

$$H_1(dd_i, pc_i) = m_i(pc_i - pc_o)^2 + \gamma a_i \int_{pc_i}^{\infty} (x - pc_i)\phi(x, pc_i)dx + n_i(pc_i - dd_i)^2$$

where $0 < pc_i \leq pc_o$.

LEMMA 4. *For any* dd_i, $H_2(dd_i, pc_i)$ *is strictly convex in* pc_i.

PROOF. Fix dd_i and take the second derivative of $H_2(dd_i, pc_i)$ with respect to pc_i:

$$\frac{\partial^2 H_2(dd_i, pc_i)}{\partial pc_i^2} = 2m_i + \gamma a_i \int_{pc_i}^{\infty} (x - pc_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx + 2n_i$$

Here, m_i and n_i are strictly positive. It can be observed that the first derivative of the expected tardiness form pc_i is a positive constant number meaning that the second derivative will be zero. Hence, H_2 is strictly convex in pc_i.

□

Let pc_i^* be the value that minimizes H_2 and k the constant that is the derivative of the expected tardiness from any pc_i. The following equation gives pc_i^*;

$$r_2(dd_i) = pc_i^* = min\left(pc_o, \frac{2m_i pc_o + 2n_i dd_i - \gamma a_i k}{2(m_i + n_i)}\right) \quad (4)$$

On contrast to the equation for dd_i^*, pc_i^* has a closed form definition. It is clear that if $2m_i pc_o > \gamma a_i k$, pc_i^* will always be greater than 0. Specifically, given Weibull distribution we assume $2m_i pc_o > a_i/(-ln(1-\theta))^{1/\alpha}$, so that pc_i^* is greater than 0 for any $\alpha(\alpha \geq 1)$ and γ $(0 \leq \gamma \leq 1)$.

4.2. Analysis of Equilibria

In this section, we relax the strategy spaces of the players and investigate the existence of equilibria for the relaxed game $(\overline{\Omega})$. We will relate results of our analysis to the original game introduced in the previous section. In the relaxed case both players' strategy spaces are identical and $\overline{\sigma}_1 = \overline{\sigma}_2 = (-\infty, +\infty)$. First, we give some preliminary results that characterize the players' best response mappings.

LEMMA 5. If $pc_i < cd_i$ *then* $r_1(pc_i) > pc_i$

PROOF. (i) In order to complete the proof we show that it is not possible that $r_1(pc_i) < cd_i$ when $pc_i < cd_i$. We can easily derive $\overline{r}_1(pc_i)$ from (3) and rewrite the inequality as follows;

$$\overline{r}_1(pc_i) = \frac{2g_i cd_i - 2n_i pc_i + a_i(1-\Phi(dd_i^*, pc_i))}{2(g_i - n_i)} < cd_i$$

which can be reduced to

$$a_i(1 - \Phi(dd_i^*, pc_i)) < 2n_i(pc_i - cd_i) \tag{5}$$

It is obvious that if $pc_i < cd_i$, the right hand side of the inequality will be negative and since the left hand side is always positive the inequality will not hold implying that $r_1(pc_i) < cd_i$ only when $pc_i \geq cd_i$. Hence if $pc_i < cd_i$ then $r_1(pc_i) \geq cd_i$ and thus, $r_1(pc_i) > pc_i$.

□

Based on the implicit function theorem, $r_1^{(1)}(pc_i)$ and $r_2^{(1)}(\mathrm{dd}_i)$ can be calculated and given as follows;

$$\overline{r}_1^{(1)}(pc_i) = -\left(\frac{\partial^2 H_1}{\partial dd_i \partial pc_i} \Big/ \frac{\partial^2 H_1}{\partial dd_i^2}\right) = \frac{-a_i \Phi^{(2)}(dd_i, pc_i) - 2n_i}{2g_i + a_i \phi(dd_i, pc_i) - 2n_i}$$

$$\overline{r}_2^{(1)}(dd_i) = -\left(\frac{\partial^2 H_2}{\partial pc_i \partial dd_i} \Big/ \frac{\partial^2 H_2}{\partial pc_i^2}\right) = \frac{2n_i}{2m_i + 2n_i + \gamma a_i k}$$

It is obvious that $0 < \overline{r}_2^{(1)}(dd_i) < 1$. Let α be the shape parameter of the Weibull distribution. For $\overline{r}_1^{(1)}(pc_i)$ we throw in the following lemma;

LEMMA 6. $-\infty < \overline{r}_1^{(1)}(pc_i) < 1$ *if* $g_i > a_i(1-\theta)/2$ *for* $\alpha \geq 1$ *and* $\theta \geq 1 - e^{-1}$.

PROOF. First, note that the denominator is positive since $g_i > n_i > 0$ and $a_i \phi(dd_i, pc_i) > 0$. In order for $\overline{r}_1^{(1)}(pc_i)$ to be less than 1 the inequality of

$2g_i + a_i\phi(dd_i, pc_i) > -a_i\Phi^{(2)}(dd_i, pc_i)$ where $\Phi^{(2)}(dd_i, pc_i) < 0$ should hold. After plugging in any Weibull distribution where $\Phi(pc_i, pc_i) = \theta$ and rearrangement, the foregoing inequality is equivalent to the following one

$$g_i > \frac{1}{2}a_i\left(\frac{dd_i - pc_i}{pc_i}\right)\phi(dd_i, pc_i) \tag{6}$$

obviously the inequality holds where $dd_i \leq pc_i$ or $pc_i < 0$, since then the right hand sight will be non-positive. Note that from Lemma 5 we know that when $pc_i < 0$, $dd_i > 0$ since $cd_i > 0$. Lets take $\left(\frac{dd_i - pc_i}{pc_i}\right)\phi(dd_i, pc_i)$ and generate an upper bound for this term for the cases where $dd_i > pc_i$ and $pc_i > 0$. Let ψ be a function defined as follows

$$\psi(dd_i, pc_i) = \left(\frac{dd_i - pc_i}{pc_i}\right)\phi(dd_i, pc_i) = \left(\frac{dd_i - pc_i}{pc_i}\right)\alpha\left(\frac{(-ln(1-\theta))^{1/\alpha}dd_i}{pc_i}\right)^{\alpha}\frac{1}{dd_i}e^{\left(-\left(\frac{(-ln(1-\theta))^{1/\alpha}dd_i}{pc_i}\right)^{\alpha}\right)}$$

This function is unimodular. After taking the first derivative of the function with respect to dd_i and equalizing it to zero, it can be shown that the value of dd_i^{ψ} that maximizes ψ should satisfy the following equality;

$$\frac{dd_i^{\psi} - pc_i}{pc_i} = \left(\alpha\left(\frac{(-ln(1-\theta))^{1/\alpha}dd_i^{\psi}}{pc_i}\right)^{\alpha} - 1\right)^{-1}$$

Knowing that $-ln(1-\theta) \geq 1$ when $\theta \geq 1\text{-e}^{-1}$, we can observe that for $\alpha \geq 1$ and $\theta \geq 1 - e^{-1}$ $1 < \frac{dd_i^{\psi}}{pc_i^{\psi}} \leq 2$ which means that $0 < \frac{dd_i^{\psi} - pc_i^{\psi}}{pc_i^{\psi}} \leq 1$ for any $pc_i > 0$. Consequently the following chain of inequalities hold

$$0 < \frac{dd_i^{\psi} - pc_i^{\psi}}{pc_i^{\psi}}\phi(dd_i^{\psi}, pc_i^{\psi}) \leq \phi(dd_i^{\psi}, pc_i^{\psi}) < 1 - \Phi(dd_i^{\psi}, pc_i^{\psi})$$

and since $dd_i^{\psi} > pc_i^{\psi}$,

$$1 - \Phi(dd_i^{\psi}, pc_i^{\psi}) < 1 - \Phi(pc_i^{\psi}, pc_i^{\psi}) = 1 - \theta$$

Hence for any dd_i and pc_i, $1 - \theta$ is an upper bound for ψ. Therefore we conclude that if $g_i > a_i(1-\theta)/2$ then inequality (5) holds and thus, $-\infty < \overline{r}_1^{(1)}(pc_i) < 1$ for any given pc_i.

□

Now we are ready to introduce the following theorem

THEOREM 1. *Assuming* $\alpha \geq 1$, $\theta \geq 1 - e^{-1}$*and* $g_i > a_i(1-\theta)/2$ *there exists a unique Nash equilibrium for* $\overline{\Omega}$. *Moreover, there is also a unique Nash equilibrium for the original game,* Ω.

PROOF. We know from Osborne and Rubinstein [17] that if the set of actions of each player is a non empty compact convex subset of a Euclidean space and each player's cost function is continuous and quasi-convex, then there exists a pure strategy Nash equilibrium. By Lemmas 3 and 4 along with the assumptions these conditions are met for both Ω and $\overline{\Omega}$ and thus,for each game there is at least one equilibrium. Let $(\overline{dd}_i^e, \overline{pc}_i^e)$ be the strategy pair at any equilibrium for $\overline{\Omega}$ and $(\overline{dd}_i^n, \overline{pc}_i^n)$ another strategy pair at another equilibrium for the same game. If $\overline{dd}_i^e > \overline{dd}_i^n$ then $\overline{pc}_i^e > \overline{pc}_i^n$ and $\overline{dd}_i^e - \overline{dd}_i^n > \overline{pc}_i^e - \overline{pc}_i^n$ since $0 < r_2^{(1)}(dd_i) < 1$. From Lemma 6 we know that under our assumptions $-\infty < \overline{r}_1^{(1)}(pc_i) < 1$ which implies that when $-\infty < \overline{r}_1^{(1)}(pc_i)$ if $\overline{pc}_i^e > \overline{pc}_i^n$ then $\overline{dd}_i^e < \overline{dd}_i^n$ should hold. This is a contradiction. Furthermore when $r_1^{(1)}(pc_i)$ is positive it is less than 1 so that if $\overline{pc}_i^e > \overline{pc}_i^n$ then $\overline{dd}_i^e > \overline{dd}_i^n$ and $\overline{dd}_i^e - \overline{dd}_i^n < \overline{pc}_i^e - \overline{pc}_i^n$ which implies another contradiction. Hence, given the foregoing assumptions the equilibrium for $\overline{\Omega}$ is unique.

Let (dd_i^e, pc_i^e) be the strategy pair at the equilibrium for Ω. With the same assumptions, if at the equilibrium for $\overline{\Omega}$, $\overline{dd}_i^e \geq cd_i$ and $\overline{pc}_i^e \leq pc_o$, then $dd_i^e = \overline{dd}_i^e$ and $pc_i^e = \overline{pc}_i^e$. The equilibrium will be unique since the all foregoing conditions are also valid for game Ω for $dd_i \geq cd_i$ and $pc_i \leq pc_o$ (*i.e.* $0 < r_2^{(1)}(dd_i) < 1$ and $-\infty < r_1^{(1)}(pc_i) < 1$).

If $\overline{dd}_i^e < cd_i$, from Lemma 5, $\overline{pc}_i^e > cd_i$. Let $b = cd_i - \overline{dd}_i^e$ and δ, η some parameters such that $0 < \delta < 1$ and $0 < \eta < 1$. Since dd_i is convex in $r_1(pc_i)$ and constrained by cd_i, marketing will have to increase her decision by b units to cd_i. As a response, manufacturing will increase pc_i by δb. The best response of marketing to this action is to move her decision either to $\overline{dd}_i^e + \delta\eta b$ or to some value that is less than $\overline{dd}_i^e$. Either points are less than cd_i and therefore marketing can't move. If marketing doesn't move, the manufacturing will not move either. Consequently at the only equilibrium, $dd_i^e = cd_i$ and $pc_i^e = r_2(cd_i)$. By using the same approach it can be shown that if $\overline{pc}_i^e > pc_o$ then $pc_i^e = pc_o$ and $dd_i^e = r_1(pc_o)$.

□

Next, we show that the total cost of the system in Ω is higher than the center's optimal solution.

THEOREM 2. *Assuming $\gamma < 1$, center's optimal solution is never a Nash equilibrium in Ω*

PROOF. Note that G_o is strictly convex. Hence, the only due date values that minimize G_o are dd_i^o and pc_i^o. If these values are equal to dd_i^e and pc_i^e respectively, then the center's solution is an equilibrium. Due to the fact that dd_i^o is strictly greater than cd_i and pc_i^o is strictly less than pc_o, if the equilibrium in Ω is observed at boundaries (*i.e.,* $dd_i^e = cd_i$ or $pc_i^e = pc_o$), the system optimal solution can't be the equilibrium. For the case where equilibrium resides within the boundaries the following equalities should hold,

$$dd_i^o = dd_i^e = cd_i + \frac{a_i}{2g_i}\Phi(dd_i^o, pc_i^o) = \frac{2g_i cd_i - 2n_i pc_i^o + a_i(1-\Phi(dd_i^o, pc_i))}{2(g_i - n_i)} \quad (7)$$

$$pc_i^o = pc_i^e = pc_o - \frac{a_i}{2m_i}\int_{dd_i^o}^{\infty}(x - dd_i)\phi^{(2)}(dd_i^o, pc_i^o)dx = \frac{2m_i pc_o + 2n_i dd_i^o - \gamma a_i k}{2(m_i + n_i)}$$

It can be straightforwardly observed that equality (7) can only hold when $dd_i^o = pc_i^o$. Hence,

$$\int_{dd_i^o}^{\infty}(x - dd_i)\phi^{(2)}(dd_i^o, pc_i^o)dx = k \text{ and}$$

$$pc_i^o = pc_o - \frac{a_i}{2m_i}k = pc_o - \frac{a_i}{2m_i}\gamma k \quad (8)$$

Since $\gamma < 1$, equation (8) is infeasible implying that $pc_i^o \neq pc_i^e$ and thus, $dd_i^o \neq dd_i^e$.

□

It may be possible for the system optimal solution to be a Nash equilibrium in Ω, only if the manufacturing is charged a_i for unit tardiness from pc_i. In other words, if $\bar{c}_i > pc_i$, marketing pays $a_i(pc_i - dd_i)$ and manufacturing pays $a_i(\bar{c}_i - pc_i)$. Note that when $\gamma = 1$, if $dd_i > pc_i$, then marketing is never charged for tardiness and manufacturing pays all tardiness penalty to the customer ($a_i(\bar{c}_i - dd_i)$) plus the tardiness penalty to the marketing ($a_i(dd_i - pc_i)$). In this case, the order can be tardy for marketing even if the outside customer is serviced in time (*i.e.* $pc_i < \bar{c}_i < dd_i$) and manufacturing still makes a payment to the marketing for being tardy.

5. Coordination in the Game

In Theorem 2, we show that competition degrades the system efficiency in the due date negotiation and capacity utilization problem. A coordination mechanism that will give necessary incentives to the departments to cooperate can lead to lower costs. Basically, the goal of the center is to initiate a contract that specifies the allotment of the revenue from the sales across marketing and manufacturing divisions in such a way that it obliterates any incentives to deviate from the center's optimal solution. To achieve this, the share of each department can be devised based on the due dates bid by the divisions, their deviation between each other, deviation of marketing's quoted due date from customer's preferences and expected tardiness for both divisions. Suppose the center distributes a fixed proportion of the revenue gained from the sale of order i among marketing and manufacturing. Let L denote that amount, $L_1 - T$ marketing's share and $L_2 + T \quad (L - L_1 - T)$ manufacturing's share. Furthermore suppose L_1 and L_2 are constant while T is a function defined as follows;

$$T = \beta_1(dd_i - cd_i)^2 + \beta_2\int_{pc_i}^{\infty}(x - pc_i)\phi(x, pc_i)dx + \beta_3 a_i\int_{dd_i}^{\infty}(x - dd_i)\phi(x, pc_i)dx$$
$$+ \beta_4(pc_o - pc_i)^2 + \beta_5(pc_i - dd_i)^2$$

T can be looked as a transfer payment to manufacturing stipulated for marketing. The objective is to determine the set of contracts, that is value ranges for the coefficients in T, such that Nash equilibrium coincides with the optimal solution. No sign restrictions are set for the coefficients and a negative value for a coefficient represents a payment from manufacturing to marketing. After the transfer payments, cost functions of the players become as follows:

$T_1 = H_1 + T$ and $T_2 = H_2 - T$

First, assume that T_1 is convex in dd_i for a given pc_i and T_2 is convex in pc_i for a given dd_i. Next we determine the allotments in which dd_i^o satisfies marketing's first order condition and pc_i^o satisfies manufacturing's first order condition. After some algebraic manipulation we produce the following equations for the coefficients that will accomplish this:

$(i)\quad \beta_1 = \frac{g_i}{a_i}\beta_3$ (9)

$(ii)\quad \beta_2 = \gamma a_i$ (10)

$(iii)\quad \beta_4 = m_i + \frac{m_i}{a_i}\beta_3$ (11)

$(iv)\quad \beta_5 = n_i$ (12)

THEOREM 3. *Assuming any Weibull distribution where* $\alpha \geq 1,\ \theta \geq 1 - e^{-1}$, $g_i > a_i(1-\theta)/2$ *and* $m_i > a_i\theta/8$ *and employing the foregoing equations there exists a unique Nash equilibrium for the new cost settings if the following inequality holds*

$$-a_i < \beta_3 < 0$$

PROOF. Following is the second derivative of T_2 with respect to pc_i for any contract that satisfies equations (9-12)

$$\frac{\partial^2 T_2(dd_i,pc_i)}{\partial pc_i^2} = -2\beta_3\left(\frac{m_i}{a_i} + a_i\int_{dd_i}^{\infty}(x - dd_i)\frac{\partial^2\phi(x,pc_i)}{\partial pc_i^2}dx\right)$$

The term inside the parenthesis is positive. To have a convex cost function for manufacturing β_3 should be negative. Given this lets also write the second derivative of the marketing's cost function with respect to dd_i

$$\frac{\partial^2 T_1(dd_i,pc_i)}{\partial dd_i^2} = (a_i + \beta_3)(2g_i + \phi(dd_i,pc_i))$$

To have a convex T_1, β_3 needs to be greater than $-a_i$. Hence, in order to guarantee the existence of a Nash equilibrium $-a_i < \beta_3 < 0$ should hold. This inequality implies that $-g_i < \beta_1 < 0$ and $0 < \beta_4 < m_i$. Granted that these inequalities hold, we can derive the following results;

$$\underline{r}_1^{(1)}(pc_i) = -\left(\frac{\partial^2 T_1}{\partial dd_i \partial pc_i} \Big/ \frac{\partial^2 T_1}{\partial dd_i^2}\right) = -\frac{a_i\Phi^{(2)}(dd_i,pc_i)}{2g_i + a_i\phi(dd_i,pc_i)}$$

$$\underline{r}_2^{(1)}(dd_i) = -\left(\frac{\partial^2 T_2}{\partial pc_i \partial dd_i} \Big/ \frac{\partial^2 T_2}{\partial pc_i^2}\right) = -\frac{a_i\Phi^{(2)}(dd_i,pc_i)}{2m_i + a_i\int_{dd_i}^{\infty}(x - dd_i)\frac{\partial^2\phi(x,pc_i)}{\partial pc_i^2}dx}$$

From Lemma 6, $0 < \underline{r}_1^{(1)}(pc_i) < 1$. If we can show that

$$2m_i + a_i \int_{dd_i}^{\infty} (x - dd_i) \frac{\partial^2 \phi(x, pc_i)}{\partial pc_i^2} dx > a_i \Phi^{(2)}(dd_i, pc_i)$$

then $0 < \underline{r}_2^{(1)}(dd_i) < 1$ which from Theorem 1 ensures that optimal solution is the unique equilibrium. For Weibull distribution the foregoing inequality is reduced to the following one:

$$2m_i > a_i \phi(dd_i, pc_i) \frac{dd_i}{pc_i} \left(1 - \frac{dd_i}{pc_i}\right) \tag{13}$$

Obviously the inequality holds where $dd_i > pc_i$. For $dd_i < pc_i$, theoretically, the maximum possible value for $\frac{dd_i}{pc_i}(1 - \frac{dd_i}{pc_i})$ is $1/4$ and for $\phi(dd_i, pc_i)$ it is θ. Hence, if $m_i > a_i\theta/8$ holds then (13) will indeed hold.

□

With these contracts the cost of deviation between division due dates are eliminated. Also, instead of paying a penalty for his own tardiness, manufacturing shares the whole tardiness penalty with the marketing specified by the selection of the coefficients according to equations (9-12). According to these contracts all parts share all the cost. Since β_3 cannot be equal to 0 or $-a_i$ (hence, $\beta_1 \neq 0$ or $-g_i$ and $\beta_4 \neq 0$ or m_i) no cost entry is solely charged to one division. Specifically, if $\beta_3 = -a_i/2$, cost for each entry is equally shared by the departments. If $L_1 = L_2$ then the revenue is also shared and as a result departments make the same profit at equilibrium. However, as β_3 increases, the marketing becomes more responsible for the due date deviation discount and the tardiness penalty while manufacturing pays the most of the capacity increment cost. The opposite happens as β_3 decreases. One can also look for contracts such that each department's cost is no greater than in the original Nash equilibrium.

6. Conclusions

In this paper, we propose a framework for coordinating the decisions of marketing and manufacturing departments within a make-to-order company. We first analyze the central model where the due date quotation and capacity utilization decisions are jointly given. Second, we investigate the decentralized case in which the departments are considered as independent decision makers. To model it, we consider a Nash game in which the departments announce their own decisions simultaneously based on their local cost structures. We characterize the basic properties of both models and comparison analysis shows that except for very special cases, the equilibrium decisions never optimize the central problem due to double marginalization. Next we propose a set of rules for the allotment of the revenue that specifies nonlinear transfer payments based on due date deviations, capacity utilization and tardiness. By these transfer payments one can achieve to implement the cooperative solution where the incentives to deviate from optimal solution are eliminated, thus, the central solution becomes the unique Nash equilibrium.

In our model we assume any Weibull distribution for the belief function that is identical across departments. In general, for any distribution who has a closed form CDF existence of equilibria can be proved as long as the capacity increment is modeled appropriately in the function using the scale parameter so that it satisfies inequality (2). For example, it could be shown that with any positive integer shape parameter Gamma (Pearson Type III) or Pearson Type V distributions as belief functions there is at least one Nash equilibrium. Equilibria exist also for Pearson Type VI distributions when shape parameters α_1 and α_2 are non-negative and $\alpha_2 > 1$. Moreover, with these distributions, the set of contracts that we propose in the previous section also provides the necessary incentives so that the optimal solution is at equilibrium. However, uniqueness of the equilibria should be further investigated for each distribution type.

Feature research may consider relaxing our assumption regarding identical belief functions and complete information in the game. In many real situations, the departments will keep their information private and as a result their belief functions will be different. The players may not have incentives to reveal their true preferences leading to a lack of trust between them which may make it very difficult to coordinate their actions. In such a case, to achieve the coordination of the departments one should develop a mechanism using appropriate transfer and/or penalty schemes so that the necessary incentives are incurred for players to announce their true preferences. In our model we restrict ourselves to a firm that never rejects an order and to customers who never cancel their orders. However in certain situations, the optimal decision for the firm may be rejection of an order for avoiding any loss of future opportunity or increased cost. Inclusion of this option, however, necessitates a state dependent analysis of due date quotation and capacity utilization management from a more strategical point. One may also attempt to include other cost factors such as inventory and earliness costs in the model which will possibly complicate the analysis.

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