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The capacity planning problem in make-to-order enterprises

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ABSTRACT

This paper addresses the short-term capacity planning problem in a make-to-order (MTO) operation environment. A mathematical model is presented to aid an operations manager in an MTO environment to select a set of potential customer orders to maximize the operational profit such that all the selected orders are fulfilled by their deadline. With a given capacity limit on each source for each resource type, solving this model leads to an optimal capacity plan as required for the selected orders over a given (finite) planning horizon. The proposed model considers regular time, overtime, and outsourcing as the sources for each resource type. By applying this model to a small MTO operation, this paper demonstrates a contrast between maximal capacity utilization and optimal operational profit.

1. Introduction

Manufacturing firms apply various policies for fulfilling customer orders. Some firms choose to fill orders through finished goods inventory. Such a policy is referred to in the literature as make-to-stock (MTS). Other firms choose to start working on an order only after it has been placed. Such a policy is referred to as make-to-order (MTO). There are a variety of MTO operations, depending on the timing the manufacturer gets involved in the product's life cycle [1]. The major difference between MTO and MTS is that MTS makes standard products using a standardized process, which do not exist for MTO at the time of capacity planning. Unlike in MTS, which hold finished goods in inventory as a buffer against variations in customer demand, MTO operations hold capacity in reserve to meet customer demand [2]. The most important aspect in MTO is the effective and efficient use of available capacity to meet customer demands. Since unused capacity represents a loss in revenue, an MTO operation manager needs to be conservative for holding their capacity.

Capacity planning determines the resources requirement of an organization to sustain a given demand over a planning horizon. There are three tiers of capacity planning in terms of their planning horizon. The long-term capacity planning focuses on yearly resources requirement of plants and divisions for new and existing product lines and processing technologies, subject to demand forecast and availability of capital investment funds. It determines (1) facility locations and plant capacities, (2) major supplier's plans and their vertical integration, (3) production technology such as new processing techniques or new automation systems, and (4) principle operation modes and production methods. The fundamentals of long-term capacity planning are mostly the same for both MTO and MTS operations.

The medium-term capacity planning focuses on setting monthly or quarterly resources requirement for each plant for typically a one-year planning horizon. It decides on workforce level, raw materials and inventory policy by product group and department. Based on sales' forecasts, it generates production capacity plans for (1) labor-employment level (layoffs, hiring, recalls, vacations, overtime, and part-timer), (2) inventory policy, (3) utility requirements, (4) facility modifications,

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(5) outsourcing, and (6) major material-supply contracts. Capacity requirements may vary from period to period in their regular time labor, overtime labor, inventory, and subcontracting.

Two conventional medium-term (aggregate) planning approaches for MTS are: (1) matching demand and (2) level capacity. With the matching demand approach, production capacity in each time period varies to exactly match the aggregate demand as forecasted for that time period, by hiring and laying-off workers. With the level capacity approach, production capacity is held constant over the planning horizon; and the difference between the constant production rate and the varying demand rate is made up by inventory, backlog, overtime labor, part time labor, temporary labor, and/or subcontracting. An MTO operation usually adopts a hybrid approach of both. On one hand, it needs to maintain a certain level of production capacity for its core competency. On the other, it cannot leverage on inventory, as every order is a backorder and it requires customization. The common practice thus is to maintain a minimum level of production capacity, and liberally relies on overtime and subcontracting to adjust its capacity and to accommodate demand fluctuation.

The short-term capacity planning sets a daily or weekly capacity plan for a planning horizon, long enough to accommodate each order's lead time. The objective of short-term capacity planning is to ensure an appropriate match between the resources availability and the capacity requirement for a production plan at the work center level [3]. For an MTO operation, it has to specify resources requirement of each labor and machine type for each customer order at its component level. Each customer order first is translated into internal orders and detailed work orders, which are then summarized into a load schedule (time-phased capacity requirements) by labor and/or equipment, in coordination with materials arrival. A typical MTO operation routinely considers the use of alternative sources such as overtime and outsourcing, in order to meet work order's deadline.

To assure a smooth production, an MTS operation usually imposes a freeze period, in which no change to the production plan can be made. In an MTO operation, however there is no freeze period imposed. An MTO manager has to constantly adjust to administrative and engineering changes to an existing order, while deciding if potential orders should be turned down or accepted into the system.

2. Problem description

This paper focuses on the short-term capacity planning problem in the MTO operation environment. In particular, this study focuses on the product mix problem, in which the MTO manager selects an optimal set of work/customer orders to maximize its operational profit over a planning horizon. Each selected order must be completed by its due date. No tardy delivery is allowed. Consequently, an MTO manager must have access to sufficient overtime and outsourcing for additional capacity to complete the selected orders on-time. The cost rate is assumed to be known for each resource and its source, though normally the cost rate for regular time is the least costly and thus should be used first, before alternative sources are considered.

The characteristics of the problem under consideration can be graphically illustrated as shown in Fig. 1. The job shop, shown in Fig. 1, includes three departments or resources, each resource may have one or more machines. Three customer orders are considered, each customer order may have its own process route. Each customer order may include several jobs (or operations) with linear precedence constraints. For example, the process route for customer order 1 is $1 \rightarrow 2 \rightarrow 3$, whereas the process route for customer order 2 is $2 \rightarrow 3 \rightarrow 2$. The processing times of the jobs on different resources are known. As shown in the example, some jobs may circulate (i.e. multiple visits to the same resource). All the three resources are available during regular time and overtime for production. In addition, subcontracting (or outsourcing) is also an option available for processing some jobs. It is assumed that the capacity of the subcontractor is large enough to fulfill any outsourcing. If we want to prevent outsourcing some jobs (i.e. the subcontractor does not have the capability), it can be easily modeled by adjusting the cost to outsource to a very large value. Although one could potentially subcontract everything, the cost of outsourcing will prevent this. It is assumed that the job that is outsourced is available at the subcontractor's facility either after the regular production time or after overtime. Resource breakdowns are not considered in this study. The selling price (or profit) of accepting an order and the order due date is given. All the accepted orders should be completed by their due dates.

The primary research objective is to formulate a mathematical model to help a MTO manager to select an optimal set of customer orders and to prescribe a schedule for each selected order such that they all are completed before their due date over a planning horizon. The model objective is to maximize the overall profit. The model helps to unify two decisions: which orders to accept and how much capacity is required of each resource in each source in order to complete an accepted order. The secondary research objective is to demonstrate the usefulness of the model by illustrating examples where conventional wisdom is not always profitable. The conventional wisdom is to maximize the utilization of the resources, but in MTO environment this does not guarantee profit maximization. The inputs to the model are the potential customer orders and their characteristics (such as process route, processing times, selling price, etc.) and job shop configuration (such as resources, their availability, etc.). The output from the model would be the list of accepted orders and their schedules.

3. Literature review

The short-term capacity planning problem for MTO operations is closely related to product mix problem, deadline setting, order acceptance, and demand/revenue management problems. Pourbabai [4] studied the short-term capacity

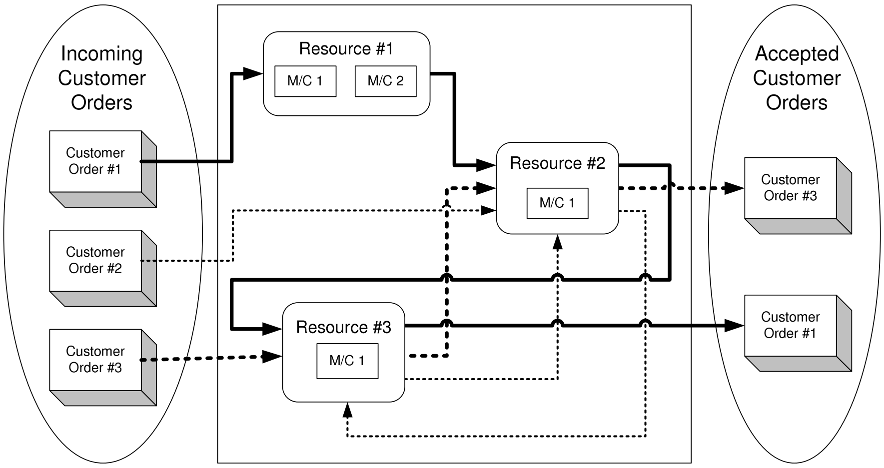

Fig. 1. Graphical illustration of the problem under study.

planning problem and presented a decision making model which accepts or rejects potential customer orders, using the group technology concept and a dispatching rule. Harris and Pinder [5] proposed a revenue management approach to plan for the capacity in an assemble-to-order manufacturing environment. Malik and Sullivan [6] developed a mixed-integer programming model to determine optimal product mix that maximizes the company's operational profit, using activity-based cost information. Li and Tirupati [7] studied the capacity expansion issues and presented an investment model to determine optimal mix of technology and capacity choices to meet a preset service level for two product families with stochastic demands.

Balakrishnan et al. [8] described how to ration the available capacity when the forecasted demand is higher than the available capacity over a planning horizon, using a decision-theory-based approach. The assumption they made was that all the products can be classified into two product classes. Lewis and Slotnick [9] proposed the use of dynamic programs and heuristics to examine the profitability of job selection decisions over a number of periods when current orders exceed capacity. They consider a penalty when not being able to meet the delivery dates. The model proposed in this paper does not allow penalties for missed delivery dates, instead the customer delivery dates/due dates are considered as hard constraints (or deadlines which cannot be missed).

In machine tool manufacturing industry the ratio of expected demand to the available capacity is assumed to be close to unity [10]. Consequently, all the orders will be accepted and when the in-house capacity is occasionally exceeded (due to short-term surge in demand) the orders are subcontracted. Barut and Sridharan [2] proposed a heuristic for short-term capacity allocation to multiple-product classes in MTO manufacturing. The objective was to maximize profit by discriminating between product classes.

Bard et al. [11] developed a nonlinear integer program to study the capacity planning problem in the semiconductor manufacturing industry and proposed the use of simultaneous equations for approximation to improve the solution quality. Bermon and Hood [12] presented a linear programming model for the product/volume mix problem to maximize long-term profit, assuming technical compatibility and cost preference exist among resources for each product type. Swaminathan [13] studied the MTO capacity planning problem under demand uncertainty and focused on using heuristics to find feasible solutions. Chou and Hong [14] formulated a mixed-integer linear programming model for the product mix problem, considering capacity allocation and lead time offset. A comprehensive review of the capacity management problem in the high-technology industry is available in Wu et al. [15].

Another critical issue for MTO operations is the due date feasibility. Because of the nature of demand, meeting an MTO due date is more than just an objective to optimize. It is a deadline to keep and thus a constraint to comply with. Due date feasibility depends on the availability of the time-phased resource capacity, as multiple orders and bids are competing for resources. Therefore meeting the deadline is the first criterion used to reject or accept a back order. The acceptance/rejection of an order based on capacity availability is referred to as available-to-promise (ATP), which is a common function in an ERP system to search and check resource availability [16].

With most ERP systems, it is a simple search in a database, accompanied by a simple heuristic rule such as first-come-first-serve (FCFS). When an order is accepted, it is usually inserted into the existing master production plan. In case when the customer deadline cannot be met, overtime or outsourcing may be considered for providing extra capacity. Özdamar and Yazgaç [17] proposed a linear capacity planning model for dealing with problems of load leveling in bottleneck departments over a planning horizon. The model's objective is to set order due dates, while minimizing total backorder and overtime costs in an MTO operation.

Kingsman [18] argued a comprehensive workload control system must consider the input of work and plan for capacity at the customer enquiry stage and proposed a general capacity planning method based on the input–output control concept. It enables dynamic capacity planning to be carried out at the customer enquiry and order entry stages for MTO companies. Holloway and Nelson [19] and Akkan [20] studied the optimal use of overtime in detailed scheduling. In their model, however, overtime was not included in the resource pool; it was used to expedite order processing instead. Therefore, the objective was to minimize the use of overtime.

Other studies also researched order acceptance policies. Keskinocak et al. [21] defined intervals to roughly filter incoming orders. Only orders that arrive within the time intervals were accepted. Duenyas [22] studied the order acceptance policy in an MRP infrastructure by considering the capacity, lead time and customer type. They established a threshold for a total number of orders allowed to be in the system. If the system has more orders than the threshold value, new orders are rejected. A classical due date problem is to schedule one machine for a set of jobs that have the same arrival time and a different processing time [23]. Solving a due date problem for even one machine may prove to be a great challenge. For example, minimizing total job tardiness on one machine remains an NP-complete problem. In a job shop environment, each order comes with a different route. The complexity makes due date problems strongly NP hard.

This paper differs from the existing literature in many aspects. The objective considered is to maximize the profit considering only the sales price and the processing costs. Each accepted order is subject to a strict deadline for delivery. Many existing literature assume a penalty for tardy jobs. The job precedence is considered and it is not restricted to a flow shop type environment. In addition to helping to decide whether or not to accept an order, the proposed model helps to develop a schedule for each accepted order. Consequently, the model takes into account the technological constraints and avoids schedule conflicts in the presence of multiple orders competing for several resources over the planning horizon. There are a number of papers which describe how to set due dates for orders in an MTO environment. However, the focus of this paper is to help an MTO operation manager to accept or reject an order, in addition to setting a delivery commitment for each accepted order. It considers resource capacity from multiple sources at a varying cost and meeting due date commitment, while maximizing its operational profit.

4. Mathematical formulation

This section presents the mathematical model proposed for the short-term capacity planning problem for the MTO operation environment. The sets used in the mathematical formulation are defined below:

I items $\{i \in I\}$
J_i jobs (or operations) in item i $\{j \in J_i\}$
T time periods $\{t \in T\}$
K resources $\{k \in K\}$
R sources $\{r \in R\}$.

The parameters used in this mathematical formulation are defined below:

s_i selling price of item i
d_i due date for item i
p_{ijk} processing time of job j of item i on resource k
c_{kr} unit processing cost per hour on resource k of source r
b_{krt} number of hours of resource k of source r available in time period t
l_{rt} number of hours of source r available in time period t.

The decision variables used in this model are given below:

X_{ijkrt} number of hours of resource k of source r assigned for processing job j of item i in time period t

$$Y_{ijkrt} = \begin{cases} 1, & \text{if job } j \text{ of item } i \text{ is processed on resource } k \text{ of source } r \text{ in time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$Z_i = \begin{cases} 1, & \text{if the order for item } i \text{ is accepted} \\ 0, & \text{otherwise} \end{cases}$$

$$O_{ij} = \begin{cases} 1, & \text{if the operation } j \text{ of item } i \text{ is outsourced} \\ 0, & \text{otherwise.} \end{cases}$$

Each order for an item may consist of several jobs (also known as operations). The jobs have precedence (i.e., job $j+1$ can begin only after job j is completed). The length of the planning horizon is fixed. Three kinds of sources are considered in this study. They are regular time, overtime, and outsourcing. The length of the regular time in one day is typically fixed and the length of the overtime can vary, depending on the need. Overtime usually is considered more expensive. The available length of both regular time and overtime is assumed to be 8 h in this study. The mathematical formulation for the problem under study is presented below.

$$\text{Maximize } \sum_{i \in I} s_i Z_i - \sum_{i \in I} \sum_{j \in J_i} \sum_{k \in K} \sum_{r \in R} \sum_{t \in T} c_{kr} X_{ijkrt} \tag{1}$$

$$\text{Subject to } \quad \sum_{i \in I} \sum_{j \in J_i} X_{ijkrt} \le b_{krt} \quad \forall k \in K, r \in R, t \in T \tag{2}$$

$$\sum_{r\in R\setminus\{|R|\}}\sum_{t\in T}X_{ijkrt}+\sum_{t\in T}X_{ijk|R|t}=p_{ijk}Z_i \quad \forall i\in I, j\in J_i, k\in K \tag{3}$$

$$\sum_{t\in T}X_{ijk|R|t}=p_{ijk}O_{ij} \quad \forall i\in I, j\in J_i, k\in K \tag{4}$$

$$\sum_{j\in J_i}\sum_{k\in K}X_{ijkrt}\le l_{rt} \quad \forall i\in I, t\in T, r\in R/\{|R|\} \tag{5}$$

$$X_{ijk|R|t}\le l_{|R|t}O_{ij} \quad \forall i\in I, j\in J_i, k\in K, t\in T \tag{6}$$

$$\sum_{j\in J_i}\sum_{r\in R}\sum_{k\in K}X_{ijkrt}\le 24 \quad \forall i\in I, t\in T \tag{7}$$

$$X_{ijkrt}\ge Y_{ijkrt} \quad \forall i\in I, j\in J_i, k\in K, r\in R, t\in T \tag{8}$$

$$X_{ijkrt}\le p_{ijk}Y_{ijkrt} \quad \forall i\in I, j\in J_i, k\in K, r\in R, t\in T \tag{9}$$

$$\sum_{k\in K}tY_{i|J_i|krt}\le d_iZ_i \quad \forall i\in I, r\in R, t\in T \tag{10}$$

$$\sum_{r'\in R}\sum_{k\in K}\sum_{t'=1}^{t-1}X_{i(j-1)kr't'}+\sum_{r'=1}^{r}\sum_{k\in K}X_{i(j-1)kr't}\ge\sum_{k\in K}p_{i(j-1)k}Y_{ijkrt} \quad \forall i\in I, j\in J_i\setminus\{1\}, r\in R\setminus\{|R|\}, t\in T \tag{11}$$

$$\sum_{r\in R}\sum_{k\in K}\sum_{t'=1}^{t}X_{i(j-1)krt'}\ge\sum_{k\in K}p_{i(j-1)k}Y_{ijk|R|t} \quad \forall i\in I, j\in J_i\setminus\{1\}, t\in T \tag{12}$$

$$\sum_{j\in J_i}\sum_{k\in K}X_{ijk|R|t}\le 24-\sum_{j\in J_i}\sum_{k\in K}\sum_{r\in R\setminus\{|R|\}}rl_{rt}Y_{i(j-1)krt} \quad \forall i\in I, t\in T \tag{13}$$

$$X_{ijkrt}\ge 0 \quad \forall i\in I, j\in J_i, k\in K, r\in R, t\in T \tag{14}$$

$$Y_{ijkrt}\ \text{Binary} \quad \forall i\in I, j\in J_i, k\in K, r\in R, t\in T \tag{15}$$

$$Z_i\ \text{Binary} \quad \forall i\in I \tag{16}$$

$$O_{ij}\ \text{Binary} \quad \forall i\in I, j\in J_i. \tag{17}$$

The objective (1) is formulated to maximize the total net profit. The first term in the objective function is the total revenue and the second term is the total processing cost. The constraint set (2) ensures that the capacity of resource k of source r in time period t is not violated. The constraint set (3) ensures that adequate resources are allocated to process job j of item i. The total number of hours allocated to process a job should be equal to its processing time. The equality constraint can be replaced with an inequality ($\ge$) constraint. The second term in the objective function will prevent allocating more resources than what is required. The first term in constraint set (3) indicates the number of hours job j is processed during regular and overtime hours. The second term reflects the hours spent on job j when it is outsourced. The constraint set (4) ensures that when a job j is outsourced, it is completely outsourced.

The constraint set (5) ensures that each item is processed for no more than l_{rt} hours in each source during each time period. If the processing time of job j is less than l_{rt}, then it is possible to start processing the next job $(j+1)$ in the same time period. Since job $(j+1)$ cannot be started before job j, the remaining time available for job $(j+1)$ in period t is only $(l_{rt}-p_{ijk})$. Consequently, the total time allocated to process item i in any time period in each source cannot exceed l_{rt} hours. The constraint set (6) ensures that when a job is outsourced, the total time allocated to process this job in each time period does not exceed the total available hours. The constraint set (7) ensures that an item is not processed for more than 24 h in any time period.

The constraint sets (8) and (9) set the Y_{ijkrt} decision variables to either 1 or 0. The Y_{ijkrt} variables are like an indicator variable; they take a value of 1 when $X_{ijkrt}>0$ indicating that job j of item i is being processed on resource k of source r in time period t, otherwise they take a value of 0. The Y_{ijkrt} variables are used to ensure the precedence relationship. The constraint set (10) ensures that when an order for an item is accepted, the completion time of the last job of that order does not exceed the order due date.

The constraint sets (11) and (12) impose precedence restrictions. Constraint set (11) ensures that job j of item i can be processed in period t only after completing job $(j-1)$. The first term in constraint (11) represents the total number of hours allotted to process job $(j-1)$ in time periods $t=1,\ldots,(t-1)$. It includes the number of hours job $(j-1)$ is processed during regular time, overtime, and outsourcing in each time period up to and including $(t-1)$. The second term in constraint (11) represents the number of hours allocated to process job $(j-1)$ in time period t. If job $(j-1)$ is completed during regular (or overtime) hours in time period t, then processing of job j can begin during regular (overtime or it can also be outsourced) hours in time period $t'\ge t$. Fig. 2 illustrates how the precedence relationship (i.e., constraint (11)) will take effect when job $(j-1)$ is completed in time period t during regular hours. The processing of job $(j-1)$ begins during the regular hours of production in time period $(t-1)$, continues during the overtime and then to regular hours of production in time period

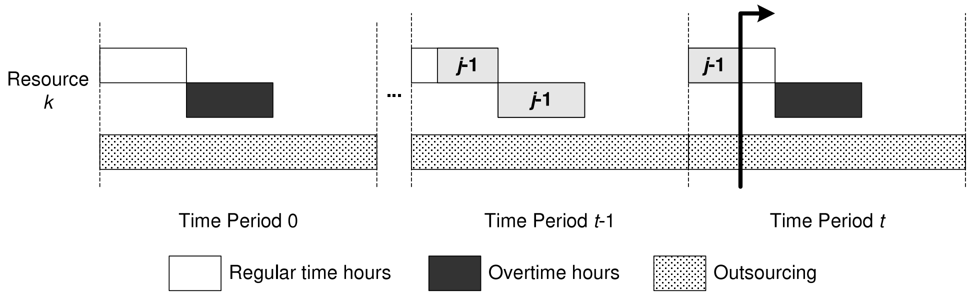

Fig. 2. Illustration for precedence constraint 11.

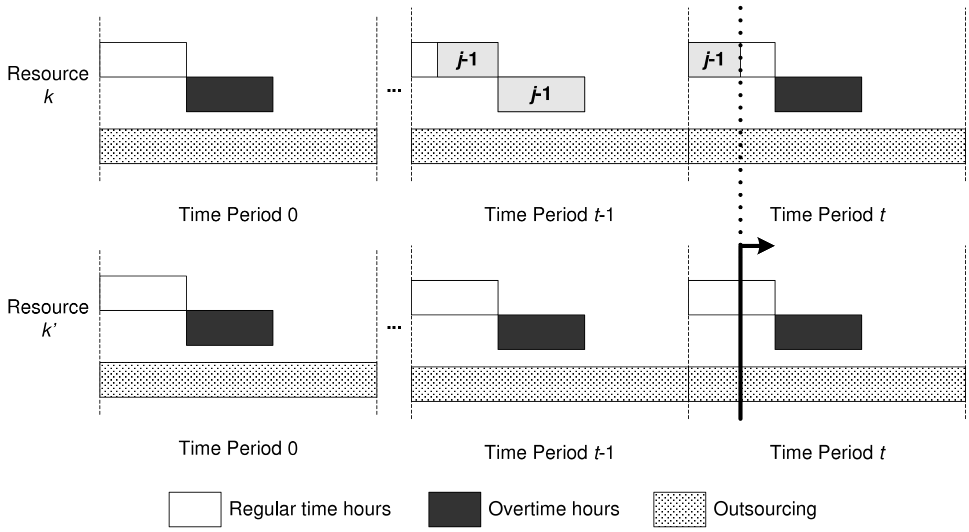

Fig. 3. Illustration for precedence constraint 11 (two different resources).

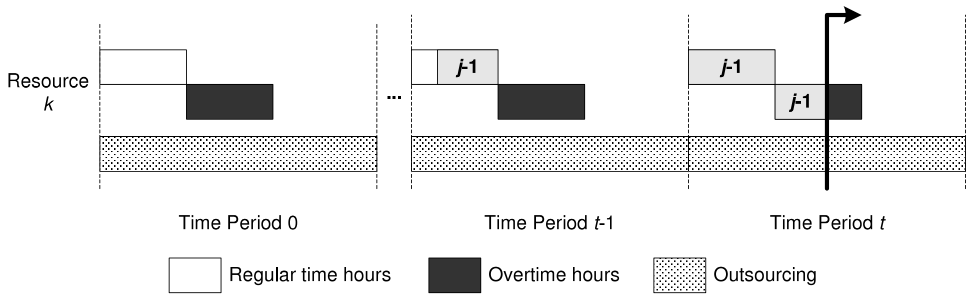

Fig. 4. Illustration for precedence (constraint 12).

t. For illustration purposes, it is assumed that jobs $(j-1)$ and j require same resource k in Fig. 2. Fig. 3 illustrates the case when both the jobs require different resources. Job j can be processed on resource k' only after job j is completely processed on resource k ($k' \neq k$).

The constraint set (12) ensures that job j of item i can be outsourced in period t only after completing job $(j-1)$. Fig. 4 illustrates how the precedence relationship (i.e., constraint (12)) will take effect when job $(j-1)$ is completed in time period t during overtime. The processing of job j can begin during the remaining overtime hours in time period t or it can be outsourced or it can be processed during any source (either regular hours, overtime, or outsource) in time period $t' > t$.

The constraint set (13) ensures that an outsourced job is processed for no more than the available time at the outsourcing facility. If job $(j-1)$ is completed during the regular time (overtime) in period t then job j can be outsourced for 16 or 8 h. The constraint sets (14)–(17) impose the non-negativity restrictions on the decision variables. The constraint sets (15)–(17) impose the binary restrictions on the decision variables Y, Z and O, respectively.

The proposed model can be solved using a mixed-integer solver, such as CPLEX, for a given problem instance. The output of the model will prescribe the set of orders to accept and a detailed schedule. The schedule will indicate which resources are committed to which jobs in each time period. A Visual Basic program is later used to determine the starting and completion times of each jobs on each resource over the planning horizon. The schedule is very useful to compute the efficiency of the

Table 1
System data.

$k \in K = \{1, 2, 3\}$	Three resource types
$r \in R = \{1, 2, 3\}$	Three sources (1: regular hours of production; 2: overtime; 3: outsourcing)
$i \in I = \{1, 2, 3, 4\}$	Four order items
$j \in J_i = \{1, 2, 3, 4\}$	Each item comprises of 4 jobs (operations)
$t \in T = \{1, 2, 3, 4\}$	A planning horizon with 4 time periods

Table 2
Resource related costs.

Resource ID	Source type ($/hr)		
	1	2	3
1	100	150	250
2	200	250	350
3	100	200	150

Table 3
Item related parameters.

Item #	Due date	Sales price ($)	Operation sequence	Resource ID	Processing time (h)	Cost estimate[a] ($)	Total cost ($)
1	4	12,000	1	2	8	800	6200
			2	3	20	2000	
			3	1	16	1600	
			4	2	9	1800	
2	4	12,000	1	2	12	2400	6700
			2	2	14	2800	
			3	3	5	500	
			4	1	10	1000	
3	4	12,000	1	2	8	1600	6600
			2	3	9	900	
			3	2	14	2800	
			4	1	13	1300	
4	4	10,000	1	1	6	600	7000
			2	1	18	1800	
			3	2	17	3400	
			4	2	6	1200	

[a] If processed in-house during regular hours.

resources, residual capacity available for future planning, and the amount of overtime and outsourcing required per time period over the planning horizon.

5. Experimentation

Tables 1–3 summarize the input data used to illustrate how an MTO operation manager could use the mathematical formulation proposed in this paper. Table 1 presents the system data such as the number of sources, resources types, item orders, jobs and time periods in the planning horizon, for the example problem used for illustration purposes. Three resource types (or machine types or resource IDs) are considered. For each resource type, three kinds of sources are considered, namely regular production time, overtime, and outsourcing. It is assumed that the regular production time and overtime is 8 h in each time period. Outsourcing runs 24 h each. There are orders for four items to choose from at the beginning of the planning horizon. Each item requires four sequential operations. The planning horizon consists of four time periods. The manager has to decide which order(s) to accept and to schedule the accepted order(s) for item(s) such that its due date can be met. The objective is to maximize the total profit, using available resources from all sources. Without loss of generality, we assume that the system has no existing jobs and thus all existing resources are available at the beginning of the planning horizon.

Table 2 summarizes the hourly rate assumed for each resource type and source type in this example. For example, it would cost $100 per hour for every hour of processing on resource type 1 during regular time and $150 per hour during overtime. In general, over time is more expensive than regular time, while outsourcing varies from one resource type to another.

Table 3 summarizes the order-related parameters used in the example. The order for all the four items considered in this example is due by the end of the fourth time period. However, each item may have different due dates in reality. This situation is considered towards the end of this section. The selling price of each item is presented in column 3. The operation sequence and the resources required for each operation is shown in the columns 4 and 5, respectively. The processing time for each operation is shown in column 6. The estimated cost to process a job during regular time in-house is shown in

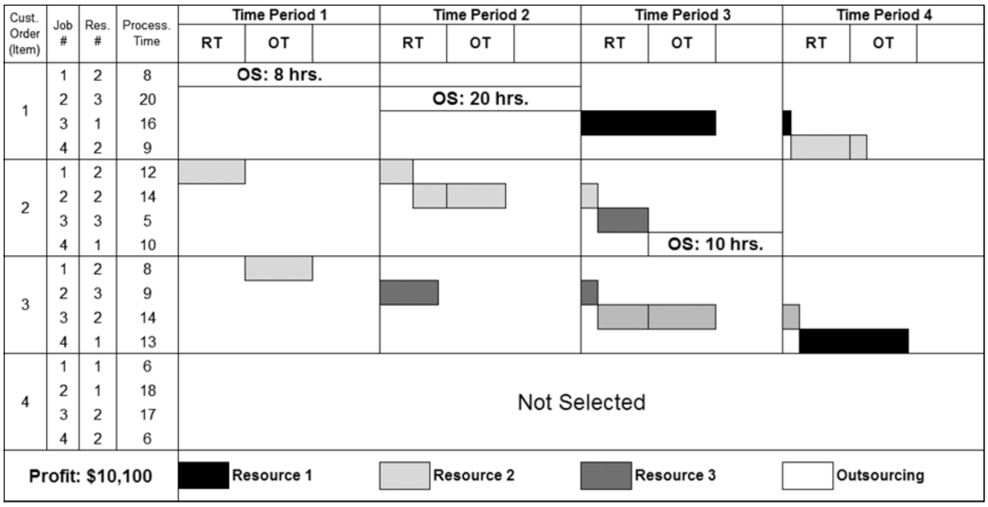

Fig. 5. Schedule for the base case.

column 7 and the total operational cost are shown in column 8. For example, the second operation of the first order needs resource type 3, and it will take 20 h to complete this operation. The estimated cost to complete this operation in-house during regular time is $2000 ($100/hr * 20). The total cost incurred to complete the order for item 1 in-house during regular time would be $6200. Consequently, if the order for item 1 is chosen, it would cost at least $6200. The cost incurred may increase if certain operations are carried out during the overtime hours or when the order is outsourced. The sales price of all the four items are assumed to be greater than the total cost of in-house production during regular hours, otherwise there is no incentive for accepting an order.

The resulting mathematical model for the above data was solved using the mixed-integer solver CPLEX. The output from CPLEX is written to a text file. A Visual Basic program is later used to translate the text file to a chart. The chart lists all the items and their operations and the schedule of all the selected orders during the planning horizon. Fig. 5 shows the schedule for the example instance under consideration. The total profit is $10,100 when the orders for items 1, 2, and 3 are accepted.

In Fig. 4, the regular (or standard time) and overtime hours are represented as ST and OT, respectively. The first operation of item 1 requires 8 h of processing on resource 2. As per the optimal results obtained from CPLEX, operations 1 and 2 of item 1 are outsourced. The remaining operations are processed in-house. Operation 3 is performed both during regular and overtime hours in period 3, and for one hour in period 4 during regular time. The last operation is performed for seven hrs during regular time and two hrs during overtime during the fourth period.

Operation 2 of items 1 and 3 compete for resource 3. The operational cost for this resource in-house during regular hours or outsourcing is cheaper than overtime hours. Consequently, preference should be given either to production during regular hours or outsourcing. The model prescribes regular time production for operation 2 of item 3 and outsourcing operation 2 of item 1. This example shall hereafter be referred to as base case. An operations manager can decide how much to bid on an order by conducting several "what if" analysis using the model proposed in this paper. Some interesting "what if" analysis is demonstrated in the following paragraphs.

Another interesting analysis would be to determine the optimal policy when the sales price of an item is increased or decreased. The sales price actually represents the bidding price for each order to an MTO operations manager. For example, if the sales price of item 4 is increased by $1000 (i.e., $11,000) the model recommends choosing orders for items 2, 3, and 4. The net profit for this policy is $11,100 and the corresponding schedule is shown in Fig. 6.

When the sales price of item 1 is increased to $13,000, all the items including item 1 are selected. The objective function value improves to $12,000. The resulting schedule is summarized in Fig. 7. The model did not prescribe to accept the order for item 4 for the base case. However, when the selling price of item 4 was increased, it prescribed to accept the order for item 4 but rejected item 1. When the selling price of both item 1 and 4 were increased, the model accepted orders for both the items. This clearly helps us to conclude that selling price or bidding price affects the capacity plan. Although all the orders can be accepted with the available resources, the model did not accept all the orders for the base case. A cursory comparison at the total cost incurred when all the items are processed in-house and during regular time with the selling price might indicate that the order for an item should be accepted. Many ERP software applications and MTO operations manager fail to take into account for the additional cost incurred when different jobs compete for same resources resulting in the usage of overtime and/or outsourcing alternatives to complete a job. By combining the order processing stage with detailed scheduling during the bidding process, the operations manager can make judicious decisions and avoid unforeseen loss.

Since sufficient capacity is available to process all the items meeting their due dates, the conventional wisdom would encourage an MTO operations manager to accept all the orders. If such a decision is made, the resulting net profit is $10,000. The resulting schedule is shown in Fig. 8. Although the utilization of all the resources is increased by accepting all the orders,

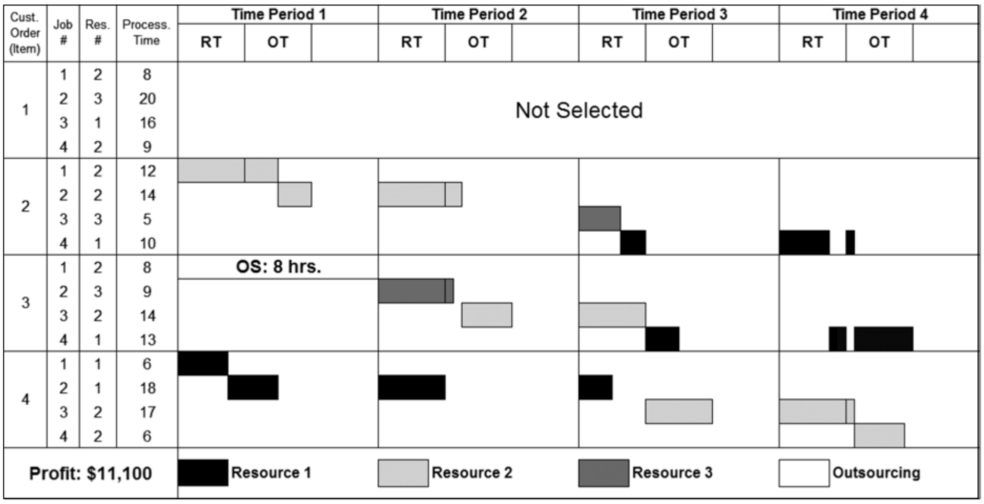

Fig. 6. Schedule when the sales price of item 4 was increased by $ 1000.

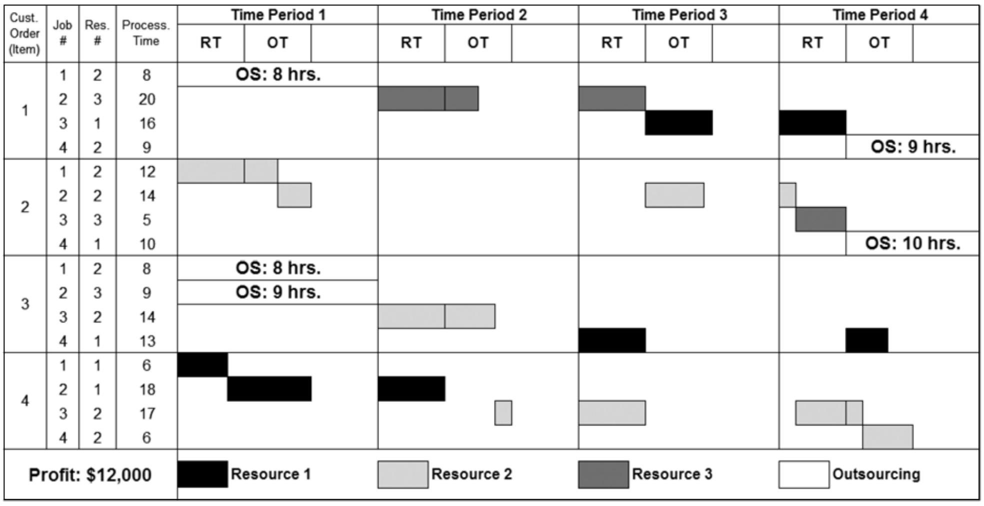

Fig. 7. Schedule when the sales price of item 1 was increased.

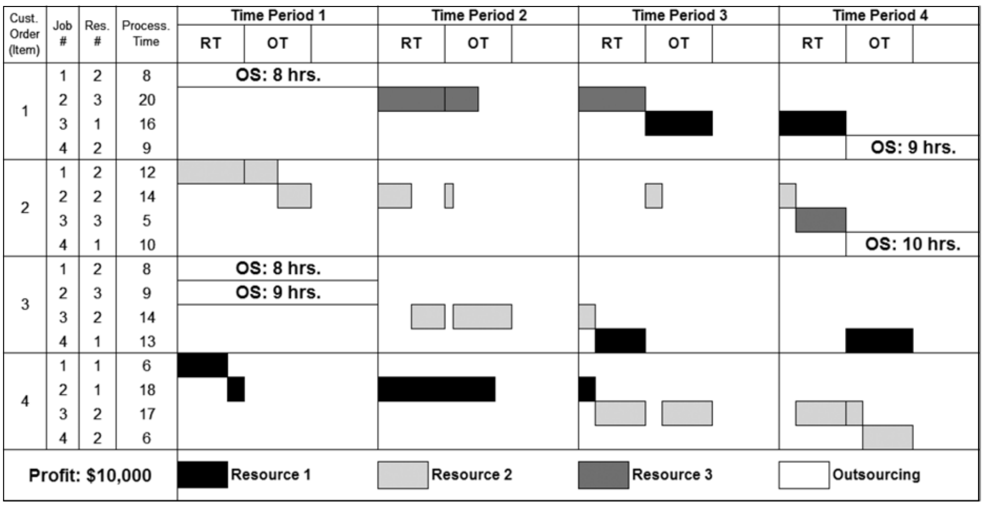

Fig. 8. Resource allocation when all the items are selected to maximize capacity utilization.

the net profit has decreased. In addition, the resources are committed to all the orders at the beginning of the planning horizon and it may not be possible to consider any orders which may arise in future time periods.

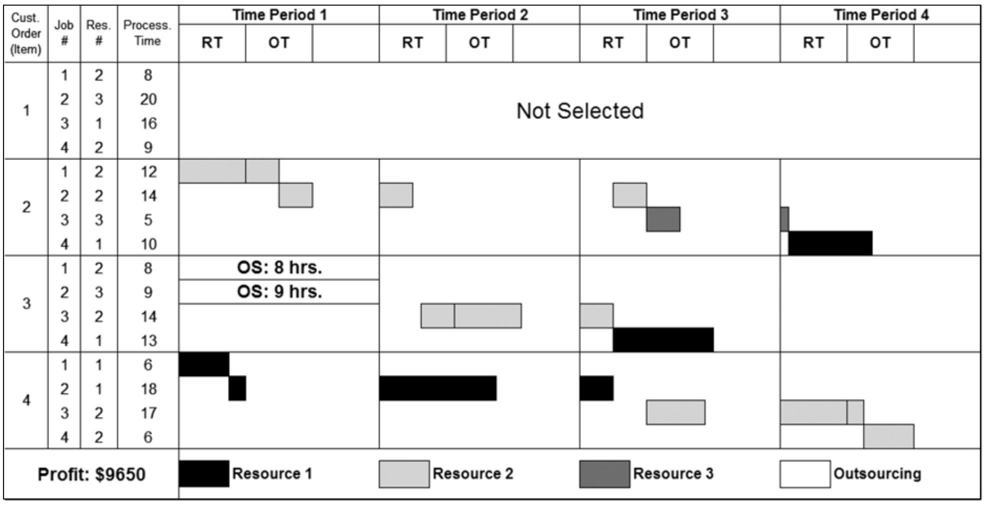

Fig. 9. Resource allocation when the due dates of items 1 and 3 are changed.

Table 4
Fixed factors and their levels.

Number of items	3
Number of time periods	6
Number of resources	3
Number of sources	3
Cost ratio for different sources (RT:OT:OS)	1:1:1.5
Processing time	Discrete uniform (3, 6)
Due dates for each item	6
Sales price for each item	$90,000

In the base case scenario it was assumed that the due dates of all the items is same. However, if the due dates of items 1 and 3 are changed to 3, the model prescribes to choose items 2, 3 and 4. The resulting profit is only $9650 and the schedule is as shown in Fig. 9. Operations 1 and 2 of item 3 are outsourced in order to meet the tighter deadlines. Fig. 10 summarizes the resource utilization for the optimal solution with the case when all the orders are accepted. These "what if" analysis demonstrates the usefulness of the proposed model, without which incorrect decisions can be made by an operations manager in an MTO environment.

The mixed integer model proposed for the problem under study can be solved using commercial solvers such as CPLEX. However, CPLEX uses a branch-and-bound approach to fix the fractional variables to integer values. Consequently, it may not be able to solve problem instances with large number of integer variables. In the model proposed, the decision variables Y, Z and O are binary. An experimental study was conducted to determine the effect of problem size on the run time (computation time) required to find an optimal solution. Table 4 summarizes the data used for this experimental study. The number of binary decision variables increases with the increase in the number of items, jobs in each item, time periods in the planning horizon, and resources. The number of sources and resources (especially for short-term capacity planning problems) will remain constant. For illustration purposes, the number of items, time periods in the planning horizon, and resources were held constant and the number of jobs per item was increased to study the effect of problem size on run time. Fig. 11 presents the problem size vs. run time plot. When the number of jobs in each item was less than or equal to 11, the run time was reasonable. However, when the number of jobs in each item increased beyond 11, the run time increased exponentially. The number of binary variables in each problem instance, when the number of jobs per item is increased, is shown in Fig. 12.

6. Conclusions

Make-To-Stock (MTS) and Make-To-Order (MTO) are the two commonly used operation modes. An MTS operation relies on demand forecast and inventory and assumes products and their processes are predefined. MTO enterprise accepts only backorders and keeps no inventory for finished goods. Product and process designs are made to customer specifications, after the order is placed. When an MTO operation engages in bidding for potential order, four questions need to be answered. They are:

(1) Does it have the technical capability to handle the order?
(2) Does it have the production capacity to accommodate the order?
(3) Can it complete the order in time for delivery?
(4) How much is the profit from the order?

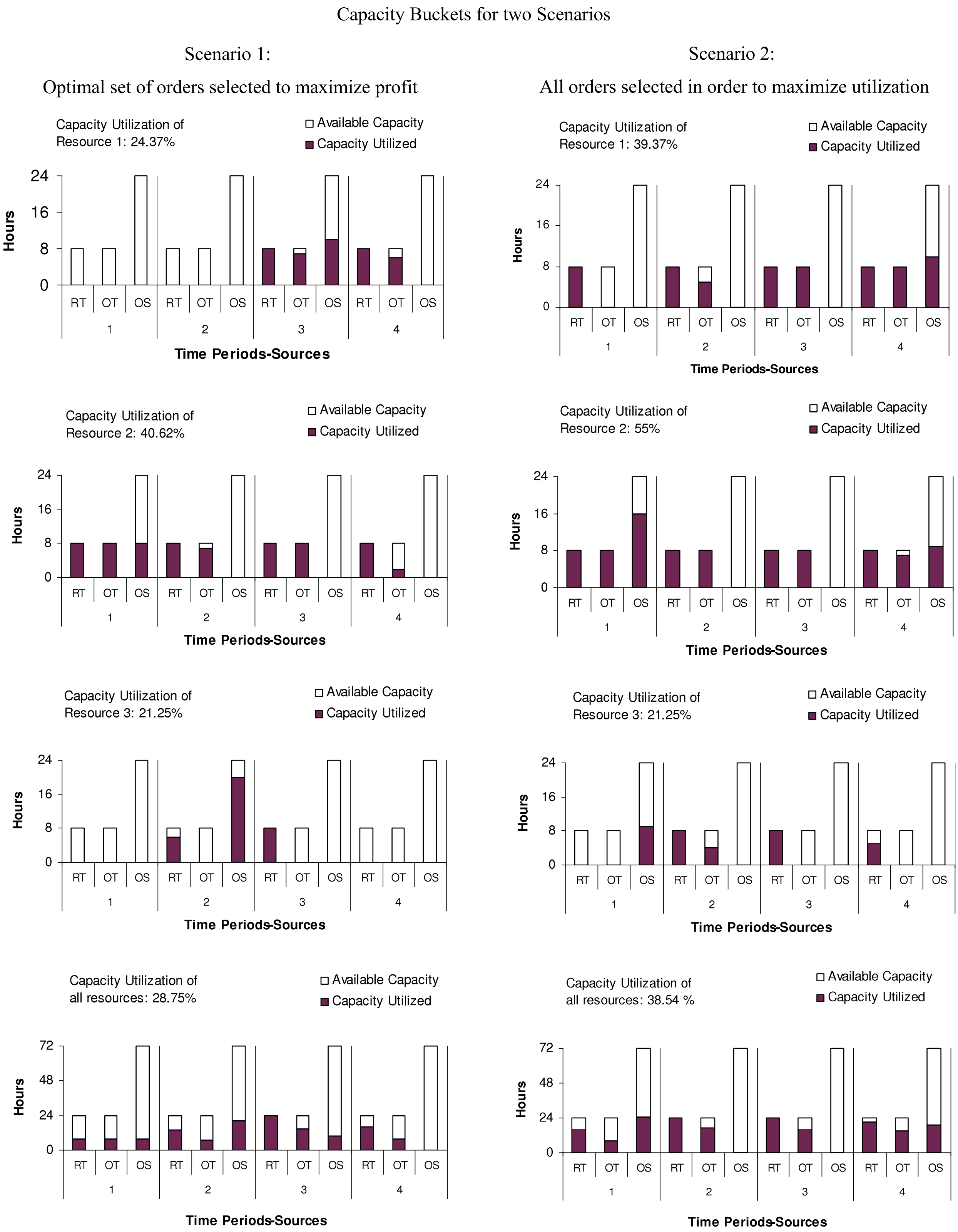

Fig. 10. Resources utilizations under the two order acceptance policies.

All four questions are closely inter-twined, while the last three are directly related to the short-term capacity planning problem. This paper addresses the short-term capacity planning for MTO and aims at an optimal answer to the above three questions.

Every MTO operation constantly faces the challenges of pricing for a bid and meeting the due date when a bid is accepted. Both challenges are closely tied to capacity requirement. This paper addresses the short-term capacity planning problem in an MTO operation environment and presents a mathematical formulation for this problem. This problem considers

Fig. 11. Solution time for different problem sizes.

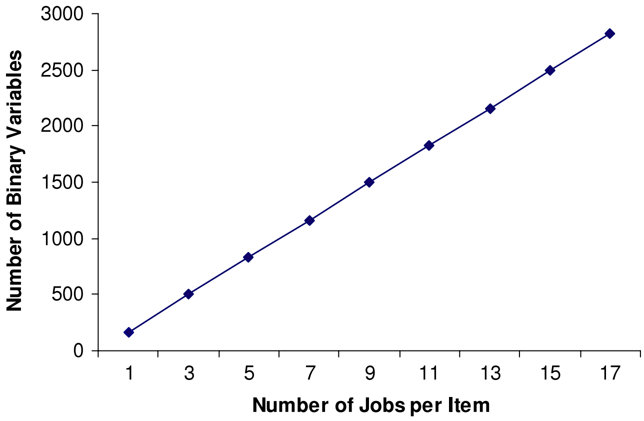

Fig. 12. Number of binary decision variables as the problem size increased with the number of jobs per item.

maximizing the operational profit by choosing the best order mix, while meeting their due dates with available resources over a planning horizon. It assumes that the operation does not have to accept all orders and no late delivery is acceptable. It considers technical precedence between jobs of an order. The model was solved using the mixed-integer program solver CPLEX for the primary purpose of model validation. Several examples were used to demonstrate the working of the model and how it can benefit a manager in an MTO environment.

This model considers overtime and outsourcing as additional resources for a variable cost. Both are vital to a typical MTO operation. The computational experience shows that the commercial system can only solve the proposed capacity planning model for small problems. More efficient algorithms are needed for solving problems of industrial scale.

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