Integrated Capacity Coordination-matching Process in Make-to-forecast Production Environments

Hamed Rafiei\textsuperscript{1a*}, Masoud Rabbani\textsuperscript{1b}, Hanan Mostaghim\textsuperscript{2c}

\textsuperscript{1}School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, P.O. Box: 11155-4563, Iran

\textsuperscript{2}Industrial and Manufacturing Systems Engineering, University of Windsor, Ontario, Canada

\textit{hrafiei@ut.ac.ir}
\textit{bmrabani@ut.ac.ir}
\textit{cmostaghh@uwindsor.ca}

Abstract: Although Make-To-Forecast (MTF) production environment is one of production systems have been utilized in real industrial world, academicians have not paid considerable attention to this field of production planning. In this paper, a novel capacity coordination framework in MTF production environments is proposed. The proposed framework includes four steps. At the first step, production value is determined based on Analytic Hierarchy Process (AHP) method upon which estimated capacity is allocated to correction process in the second step. Next, product lot sizes are optimized in the third stage using a proposed mathematical programming model. The final step is related to order acceptance/rejection and matching process. In this regard, negotiability of receiving orders is considered in order to make proper acceptance/rejection decision. Also, an assignment model is developed for the matching process, which is tackled using the well-known Hungarian method. Finally, results of a real-world industrial case study are reported to show performance of the proposed framework.

Keywords: Capacity coordination, make-to-forecast, matching process, order acceptance/rejection, production planning

1 INTRODUCTION

Different manufacturing companies adopt different production strategies ranging from make-to-stock (MTS) to make-to-order (MTO). In MTS production context, products are processed based upon demand forecasts which are responded using stocked end products. Thus, customer lead time is short and setup costs are low in such systems; however, due to low level of interaction with customers in MTS systems, product customization is very low and holding cost is high. MTS strategy is usually used in production systems which process the products that are not very expensive. Moreover, it is not a good idea to adopt this policy when demand is highly fluctuating, since it is too difficult to forecast. On the other hand, MTO production systems are based on customer orders, where there is no production until specific orders are received. As there is high interaction between customers and production in MTO systems, high level of customization is satisfied in the products. Upon the fundamentals of MTO production strategy, no finished goods inventory is kept in such systems. Therefore, customer lead time is longer than that of MTS to cover all production stages, resulting in higher level of order backlog. This strategy is usually utilized for low volume, high variety
products. Moreover, it makes manufacturing setups necessary, since different products are processed in MTO system [1].

Today’s competitive market enforces manufacturing systems to deliver the products with higher level of customization within shorter delivery lead time. Hence, academicians and practitioners attempted to take advantages of both MTS and MTO strategies, simultaneously, to cope with customization and responsiveness in the production systems, leading to introduction of hybrid production strategy. Hybrid production strategy permits an acceptable level of customizations with reasonable delivery time [2]. MTF production strategy is a kind of hybrid MTS/MTO production strategies. This strategy is useful for companies producing large and heavy engineered equipment, such as pressure vessels, mainframe computers and construction equipments. MTF strategy was firstly introduced by Raturi et al. [3]. This strategy was introduced for the environments in which it is not possible to store large end products. In this kind of strategy, delivery lead time is shorter than production lead time and the speed of production is not too varying. In this regard, different combinations of component variants are forecasted, upon which production process is started and continued until receipt of orders; next, it is attempted to match the received orders with eligible units. Although MTF is a kind of hybrid MTS/MTO strategy, there are some major differences between them. First, MTF rules allow customization from the beginning of the production, while in MTS/MTO strategy, no customizations are allowed before receipt of orders. Furthermore, customizations are done at higher degree compared with MTS/MTO strategy. Also, in MTS/MTO, production process stops at a particular point and work-in-process (WIP) inventories are held until orders are received; however in MTF environment, it is based on matching the orders with the producing units or WIP inventories.

In hybrid strategy, it might be the most challenging issue to keep balance between responsiveness and customization, which makes it more complex than the two pure strategies of MTS and MTO. To tackle the inherent complexity, Hierarchical Production Planning (HPP) is proposed, by which relevant decisions of the system is partitioned into some levels of decisions with specific characteristics and different planning horizons. HPP approach was firstly introduced in the field of production planning by Hax and Meal [4]. This approach has been recently adopted by Ashayeri and Selen [5], Soman et al. [6] and Rafiei and Rabbani [7] in the field of MTS/MTO production systems. They utilized HPP approach to divide production planning issues of MTS/MTO systems into simpler sub-problems which are properly interacted with each other. Generally in a hierarchical structure, outputs of upper decision levels play roles of constraints in the lower levels; whilst there is a feedback structure from lower decision levels to the upper ones [8]. An HPP structure includes three levels of strategic, tactical and operational decision making. The strategic level involves long-term planning including capacity coordination, and finally, the operational level comprises short-term detailed planning, such as production controlling and scheduling [9, 10]. As the tactical decision of the HPP, capacity coordination is the main focus of this paper. Capacity coordination seeks to balance between capacity and demand on the basis of customer demand forecasts, available capacity, on-hand orders and coming orders in order to maximize total profit of the system [11]. In this regard, the main objective of this paper is to develop a framework to cope with the complexities of capacity coordination in MTF production environments. To do so, some sub-objectives are regarded in this paper. These sub-objectives include prioritizing coming orders, setting proper feasible due dates, making acceptance/rejection decisions of coming orders, and determining lot sizes of productions. It is noted that capacity coordination is one the most challenging issues with which MTF systems deal. If improper capacity coordination is implemented, high level of finished-product inventories without buyer (known as orphans) are stocked, while in the case of inadequate capacity, many orders cannot be accepted and a great amount of chance will be lost in order to gain profit.

Remaining of the paper is as follows. Section 2 briefly reviews literature of MTF production systems and the related aspects, while the proposed capacity coordination framework is elaborated in Section 3. Results of the proposed framework in an industrial case study are reported in Section 4 and Section 5 provides some concluding remarks and future research directions.

2 LITURATRE REVIEW

There are only handful research papers devoted to the MTF production environment. The first paper in the field of MTF backs to 1990 by Raturi et al. [3]. They proposed this strategy in order to enhance customization opportunities, while response times of their coming orders are reduced in a case of machine tool industry. By means of this mechanism, similar parts and sub-assemblies are used in manufacturing of different products. In their paper, three case studies were presented and their
operational and managerial problems were discussed. Finally, they concluded three mechanisms to cope with the problem; simplification of products/production process, reducing demand/supply risks, and providing engineering/manufacturing slack. The research direction introduced by Raturi et al. did not receive attention of academicians for more than a decade, when two pieces of research were published. Akinc and Meredith examined an MTF system concerning the level of orphan products and the rejected orders. In order to perform the analysis, they utilized Markov process approach to select proper capacity of MTF environments [2]. Also, Meredith and Akinc presented a thorough description of MTF production policy and scrutinize different decision rules of matching arriving orders to in-process units. They proposed a discrete simulation model which was applicable for various manufacturing systems with different assumptions. It also helps managers to handle the matching problem in an easier way. Finally, they concluded that more complex matching rules with more factors were able to considerably improve MTF performance and increase firm profitability [12]. Overall, the main dilemma of the MTF production is balancing between shortening delivery time and enhancing level of customization.

Characteristics of different production strategies have been more explored after some papers devoted to the impacts of customer order decoupling point. Two impressing samples of such research papers are the ones by van Donk [13] and Olhager [14]. van Donk analyzed the relationship between production system and decoupling point. Also, he introduced eight factors within two categories of Product and market, and process and stock to locate the decoupling point [13]. Olhager extended van Donk’s criteria into three categories of market, product, and production [14]. Furthermore and in order to cope with the complexities of production planning in hybrid systems, Soman et al. introduced the concept of HPP in the field of hybrid production systems. In this regard, they divided the involved issues in the system into three levels (strategies, tactical, and operational) for which relevant questions were developed. Then, they validated their developed framework in a case of food industry. Among the introduced questions, capacity coordination might be the most challenging one in the tactical level, which addresses how the capacity is managed in order to enhance firm profitability [6]. In this regard, the first capacity consideration in MTO environment is related to the papers by Ebadian et al. [15] and Ebadian et al [16]. The authors presented an acceptance/rejection framework by considering price and raw material supplier selection. To do so, they presented two mixed-integer linear programming models. In another research paper [7], Rafiei and Rabbani proposed a capacity coordination framework for hybrid MTS/MTO environments. In a more complex manner, their proposed framework tackled three major challenges of hybrid systems; MTO and MTS/MTO order acceptance/rejection, MTS lot optimum sizes, and system required capacity. It was assumed that the considered system includes MTS, MTO and MTS/MTO products among which negotiable and non-negotiable orders are distinguished. Also, they developed a heuristic algorithm to calculate lot sizes of MTS products. Finally, the proposed framework was implemented in a real case study in the field of wood industry and presented improvements obtained after the framework had been implemented. Next, Rafiei et al. extended their previous tactical framework into a bi-level hierarchical structure including tactical and operational levels. In the operational level, production sequence of MTS lot sizes and accepted MTO and MTS/MTO orders are determined using a developed particle swarm optimization algorithm [11].

From another point of view, since the problem in this paper is related to the concept of delayed product differentiation, three relevant research papers are also reviewed [17, 18, 19]. Lee and Tang developed a model which sought to capture costs and benefits of delayed product differentiation. They considered costs of process design, product processing, and inventory of intermediate stages. The considered production system was a serial line with uncapacitated buffers at every production stages. Also, it was assumed that adequate safety stock was replenished and product demands follow normal distribution. Moreover, three cases of standardization, modular design, and process restructuring were analyzed upon the results obtained from the developed model [17]. Similar studies were reported by Gupta and Benjaafar [18] in a serial production line with two different assumptions; load dependent lead times and limited buffers at intermediate stages. As a case of delayed product differentiation, Kim and Chhajed introduced “parts commonality” and “modular product design”. They developed a mathematical model to determine under what conditions commonality help the firms increase revenue within a market of two high and low segments differentiated upon quality levels of two products [19]. The concept of product modularity or delayed product differentiation is similar to that of MTF, because all of them refer to distinguishing specific orders from common production stages as late as possible in the production line. However, the above
mentioned research papers were mainly devoted to the strategic decision of whether adopt delayed product differentiation or not, while this paper concentrated on developing a tactical-level framework towards capacity coordination in MTF production systems. Therefore, the use of MTF is not the concern of this paper and a specific decision is of interest, while the MTF production strategy is assumed to be adopted in advance.

Concluding from the literature, a few studies have been conducted in MTF production systems, by which some major questions of MTF systems have not been yet responded. One of the major issues is capacity coordination which is mainly addressed in this paper, while some sub-problems are addressed in shadow of this decision. The coming orders are prioritized; order due dates are determined; it is decided to whether accept or reject the orders; orders are matched with the WIPs; and production lot sizes are optimized. Hence, the main contribution of this paper is introducing concept of capacity coordination to the field of MTF production planning for the first time. In this regard, a framework is developed in order to tackle relevant decisions of the tactical level of HPP in MTF production systems.

3 PROPOSED CAPACITY COORDINATION FRAMEWORK

In this section, an MTF production system is considered, which solely includes MTF products. In other words, production starts on the basis of the order forecasts as occurs in MTS production systems. Then, received orders are matched with the semi-finished products (WIPs) in order to respond the orders. Also, it is assumed that the considered MTF production system is implemented in a flow-shop production system in which products are processed in batches. The assumption of batch processing is different from the assumption of single-unit processing in [12]. Similar to the model of [12], periods are short (week or day). Each unit is released to the production line base on its planned bill of assembly [12]. It is assumed that estimation for future orders is available, because it is out of scope of this paper. However, the orders arrive randomly and they ought to be matched to the existing units in the line with the higher priority with the units nearer to the end of production line. This section describes the proposed capacity coordination framework for the above mentioned production system. In the proposed framework, production values of the products are calculated using the AHP method. Portions of capacities remains unfilled for the coming orders in future to be met from corrected in-process units. Product lot sizes of the forecasted in-process demands are optimized. Then the developed framework towards order acceptance/rejection is described for the negotiable and non-negotiable orders. Steps of the proposed framework are described in the followings. Figure 1 illustrates the steps as well as their relations.

3.1 Step 1: Determining Production Values of the Products

In this step, production values of all products are
calculated using the well-known AHP method [20] whose structure is shown in Figure 2. The criteria which are used in the proposed structure include estimated contribution, potential purchasing, market share, reputation, and expected cost to change. The proposed criteria consider both market side and manufacturing side of the MTF production system (estimated contribution, potential purchasing, market share and reputation as marketing criteria, and expected cost to change as a manufacturing criterion).

In order to calculate production values of products, following comparison matrix is used. Based upon the matrix, production values of products are obtained as the final weights of the following comparison matrix. In this matrix, \( a_{ij} \) is the weight of product \( i \) with respect to criterion \( j \), which is assigned using the scale presented in Table 1. In other words, this step prioritizes the coming orders with respect to some qualitative criteria and upon the judgments of experts.

\[
A = \begin{bmatrix}
    a_{11} & \cdots & a_{1n} \\
    \vdots & \ddots & \vdots \\
    a_{n1} & \cdots & a_{nn}
\end{bmatrix} \quad \Rightarrow \quad W = \begin{bmatrix}
    \sum_{j=1}^{n} a_{ij} \\
    \sum_{j=1}^{n} a_{ij} \\
    \sum_{j=1}^{n} a_{ij} \\
    \sum_{j=1}^{n} a_{ij} \\
    \sum_{j=1}^{n} a_{ij}
\end{bmatrix} / n
\]

Table 1. Pair-Wise Comparisons’ Scale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>A little important</td>
</tr>
<tr>
<td>5</td>
<td>More important</td>
</tr>
<tr>
<td>7</td>
<td>Much more important</td>
</tr>
<tr>
<td>9</td>
<td>Absolutely more important</td>
</tr>
</tbody>
</table>

3.2 Step 2: Allocating Correction Capacity to Incoming Orders
It is necessary to allocate some amount of firm’s capacity for correction process with respect to the future coming orders. In other words, this capacity remains unfilled until an order is received, then the allocated capacity is utilized to conduct the required correction to in-process units in such a way that the requirements of the received order are fulfilled. This capacity is identified according to the historical data and experts’ judgments.

3.3 Step 3: Determining Product Lot Sizes
Since production requires setups in the considered system, product lot sizes are optimized in this step. To do so, a mathematical model proposed based upon demand forecasts of the products. The nomenclature and the proposed model are presented in Appendix A. In the proposed mathematical model, product lot sizes are optimizes with respect to the operational costs in regular and overtime, setup times and costs, holding and backlog costs and the product values (calculated in Step 1). In this regard, time capacity of the bottleneck of the system is considered as the constraint to determine how setups should be performed.

3.4 Step 4: Accepting/ Rejecting Orders And Matching In-Process Units
Having lot sizes of in-process products calculated, it is decided to accept or reject the coming orders. To do so, orders are categorized into two main categories; negotiable and non-negotiable orders. Since these two categories are different, different acceptance/rejection procedures are proposed as described in the followings

a) Non-negotiable orders: In order to accept/ reject non-negotiable orders, the shown procedure in Figure 3 is proposed. The proposed procedure is based upon assessing order due dates, WIP availability, and raw material availability. Sections 3.4.1 to 3.4.5 describe details of the proposed
acceptance/rejection procedure for the non-negotiable orders.

3.4.1. Assessing due date
First, it is checked whether there is enough time to deliver incoming orders on their due dates. To do so, statement (1) is utilized [21]:

\[ LST_l = DD_l - DLT_l \]  

(1)

where \( DD_l \) and \( DLT_l \) are due date and delivery lead time of order \( l \). If \( LST_l \) is greater than the acceptance/rejection period, there is enough time to process the order; otherwise, the order is rejected.

3.4.2. Checking in-process units
After checking possibility of producing the incoming order with respect to its due date, the possibility of order processing is checked with respect to the available in-process units. Following equation checks this availability [22]:

\[ \sum_{t}^{T} N_P_l \times P_t \leq R\_U_t + R\_U^\prime_t \quad t \in \{1, \ldots, T\} \]  

(2)

In above equation, \( N_P_l \) is the number of products in order \( l \); \( P_t \) shows the acceptance probability of order \( l \) (calculated as in Equation (4)); \( R\_U_t \) represents the number of unmatched in-process units in period \( t \) which are remained from period \( t-1 \); and \( R\_U^\prime_t \) is the number of units whose processing is started in period \( t-1 \) and are available for matching in period \( t \). If the customer’s order does not match with any units, order processing is evaluated from the beginning of the line (refer to Section 3.4.3); otherwise, the most proper units are identified to match with the order. The units with which the order is matched includes three kinds of units; (a) available unmatched units which are being processed in production line, (b) available unmatched units stocked, and (c) units matched with the previously accepted orders that have not been yet processed.

3.4.3. Checking the possibility of processing the unmatched order from the beginning of the line
In this regard, production possibility is evaluated using Equation (1). Next, it is assessed with respect to resource adequacy using a rough-cut capacity check. In order to check the capacity adequacy, Equation (3) is proposed:

\[ P_t \times RCAP_j \leq \sum_{j=1}^{k} REGCAP_{j0} \quad \forall j \in R(i) \]  

(3)

where \( RCAP_j \) is the required capacity of resource \( j \) for producing order \( l \); \( P_t \) shows the acceptance probability of order \( l \) which is calculated as follows [23]:

\[ P_t = \begin{cases} 1 & \text{if } d_t - TCAP_l \leq 0 \\ \frac{1}{1 + \beta_0 \cdot \exp \left( \frac{d_t - TCAP_l}{CCAP_l \cdot TCAP_l - 1} \right)} & \text{otherwise} \end{cases} \]  

(4)

In Equation (4), \( c_l \) and \( d_t \) are the cost and the delivery time of order \( l \). \( TCAP_l \) shows total required capacity for order \( l \). \( CCAP_l \) is the unit cost of capacity, while \( \beta_0, \beta_1 \) and \( \beta_2 \) are the demand parameters of order \( l \) determined based on historical data or experts’ opinions (these parameters are elicited upon the initial demand forecasts; for more explanation, readers are referred to [23]). Using Equation (3), if the capacity is adequate, the order is accepted; otherwise, the capacity increase is considered. In order to assess whether to increase the capacity, cost of capacity increase and the order acceptance margin are compared in order to decide whether capacity increase is profitable. Hence, the order is accepted when the capacity increase is profitable; otherwise, the coming order is rejected.

3.4.4. Determining the proper unit for matching process
The proposed matching rule in this paper is based on the order net contribution. That means it is tried to match the incoming orders with the units which increase the net contribution. These units can be either the unmatched units or the previously matched units which have been not processed yet. In this regard, Meredith and Aknic proposed a local optimal assignment problem to match the order to the unmatched units [12]. Their model optimizes the problem locally, because matches of each period are made only for that period. The model presented in Appendix B is proposed to find the best matching process between the incoming orders and the units (unmatched units or the previously matched). The matching process in this paper is developed upon the model proposed in [12] with some modifications. The model proposed in [12] considered single-unit processing in every period at every workstation by two-dimension variables; however, the model in this paper allows lot sizing of the orders using three-dimension decision variables.

With respect to the model presented in Appendix B, if it is decided to match the unmatched units with the received order, it is required to check availability of the raw materials to be supported to change components of the units. On the other hand, if it is decided to match the previously matched units with the received order, it is necessary to find some unmatched units instead of the matched units.
the unmatched orders. The above explained matching process is repeated until all received orders of the current period are decided. Upon the matching process, an order is matched with some in-process units, or it is rejected, because there are no in-process units available to be matched with the received order. After finding the best units to match with incoming orders, the availability of required raw materials are checked.

3.4.5. Checking the availability of raw materials

In order to verify the availability of raw materials which are required for components changing process, following formula is utilized [22]:

\[
\sum_{i=1}^{n} N_{i} P_{i} \leq \frac{(MR_{rt} + RM'_{rt})}{RM_{rt}} \quad \forall r = 1,...,R, t \in \{t_{max},...,T\}
\]

where \(RM_{rt}\) is the number of the \(r^{th}\) raw material that are bought at period \(t\); \(RM'_{rt}\) shows the number of the \(r^{th}\) raw material remained from period \(t-1\) to be used in period \(t\); \(RM_{rt}\) is the consumption rate of the \(r^{th}\) raw material in each unit of the order. If the available raw materials are sufficient, the order is accepted. Otherwise, the incoming order is rejected.

in previous stage. In other words, in the latter case, the previously matched orders are now unmatched, for which some new units should be selected. To do so, another mathematical model is proposed (for the detailed explanation, refer to Appendix C), by which it is determined what units are matched with

a) Negotiable orders: The proposed acceptance/rejection procedure for negotiable orders is similar to that of the non-negotiable ones with some minor differences which are explained herein. First, in the case of insufficient time to deliver orders (regarding

Fig. 4. The proposed acceptance/rejection procedure for the negotiable orders

Fig. 5. (Cont’d). The proposed acceptance/rejection procedure for the non-negotiable orders

Fig. 6. The proposed acceptance/rejection procedure for the negotiable orders (Cont’d)
their due dates within Section 3.4.1), new due dates are negotiated with the customers. Second and in the case of insufficient capacity, when capacity increase is not profitable, new order prices are negotiated. Similarly, the order prices are negotiated when procurement of the excess raw materials is not profitable. Overall, it is concluded that in the case of negotiable orders, order features (price, or due date, or both of them) are negotiated so as to make the production feasible and profitable with respect to time and capacity. If the new features are accepted by the customer, the order is accepted; otherwise, it is rejected. The proposed acceptance/rejection procedure for the negotiable orders are demonstrated in Figure 7.

![Figure 7. The proposed acceptance/rejection procedure for the negotiable orders (Cont'd)](image)

related to capacity coordination issues, the proposed model has been developed and applied to the factory. Followings present a brief description of the results of the proposed framework in the factory.

### 4.1 Case Data
The factory produced six different kinds of molds including Type 1, 2, 3, 4, 5, and 6. The production line of the products comprised 9 workstations through which the process was conducted (all workstations were not used for all products). Process data of the line are presented in Table 2, which include setup and processing time for each product in each workstation (numbers in parentheses are the setup times). In addition, production cost in regular time and overtime and setup cost were 20, 25, and 15 for any product.

The considered planning horizon was one month (four weeks, 5 days a week and 7 hours a day) which was equal to 8400 minutes of regular time. The overtime was at most 2 hours (120 minutes) per day. Moreover, warehouse capacity and the amount of raw materials were assumed to be sufficient. Table 3 shows estimated delivery dates of the products, their holding and backlog costs and their prices.

### 4.2 Determining Production Values of Products
Based on the hierarchical structure in Figure 1 for the products, the production value of each product was calculated using Expert Choice® software. These values are presented in Table 4.

### 4.3 Allocating Correction Capacities
Correction capacities were allocated upon the production experts’ judgments. In this regard, Table 5 shows the remaining capacity after allocation.

### Table 2. Processing and Setup Times (Minute)

<table>
<thead>
<tr>
<th>Products</th>
<th>Workstation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>24(4)</td>
</tr>
<tr>
<td>2</td>
<td>32(4)</td>
</tr>
<tr>
<td>3</td>
<td>51(8)</td>
</tr>
<tr>
<td>4</td>
<td>48(8)</td>
</tr>
<tr>
<td>5</td>
<td>38(6)</td>
</tr>
<tr>
<td>6</td>
<td>32(5)</td>
</tr>
</tbody>
</table>

### Table 3. Products’ Information

<table>
<thead>
<tr>
<th>Delivery date</th>
<th>Holding cost</th>
<th>Backlog cost</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>355</td>
<td>9165</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>250</td>
<td>8595</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2214</td>
<td>7395</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>2574</td>
<td>8985</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>1155</td>
<td>9850</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>1056</td>
<td>7056</td>
</tr>
</tbody>
</table>
Table 4. Production values of the products

<table>
<thead>
<tr>
<th>Product type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production value</td>
<td>0.269</td>
<td>0.207</td>
<td>0.133</td>
<td>0.087</td>
<td>0.158</td>
<td>0.145</td>
</tr>
</tbody>
</table>

Product types 2 and 3 was not sufficient, the remaining amount to meet Order 1 was built from the beginning of the line. Checking the due dates in this case showed that there was no enough time to process the order. Therefore and upon the flowchart in Figure 5 for non-negotiable orders, it was decided to reject Order 2 and match Order 1 with Product types 2 and 3, instead. About the third order, Order 3 was accepted because there were enough time and in-process units to fulfill the order.

In the case of the fourth order and the results of the matching procedure, Order 4 was matched with Product types 5 and 6. It is noted that matching procedure was considered for both Orders 4 and 5, simultaneously, since Order 4 had not been processed yet. The obtained results matched Order 4 with Product types 4 and 5; while Order 5 was matched with Product types 4 and 6. Hence, there were five units of Product type 4 remained. Having the available units required for Order 6 checked, it was shown that two units of Product type 4 should have been produced from the beginning of line so as to meet the required units of Order 6. In this regard, the proposed assignment model was solved upon the Hungarian method using a developed code in MATLAB software. Also, rough-cut capacities were calculated for Resources 1, 2, and 6 to 9. Corresponding results are presented in Table 8.

Table 5. Capacity (Minute) after allocating correction capacity

<table>
<thead>
<tr>
<th>Resources</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction Capacity</td>
<td>800</td>
<td>1080</td>
<td>918</td>
<td>1250</td>
<td>688</td>
<td>2300</td>
<td>2300</td>
<td>765</td>
<td>1100</td>
</tr>
<tr>
<td>Total Capacity</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
<td>8400</td>
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<tr>
<td>Remaining</td>
<td>7600</td>
<td>7320</td>
<td>7482</td>
<td>7150</td>
<td>7712</td>
<td>6100</td>
<td>6100</td>
<td>7635</td>
<td>7300</td>
</tr>
<tr>
<td>Remaining per day</td>
<td>380</td>
<td>366</td>
<td>374</td>
<td>357</td>
<td>385</td>
<td>305</td>
<td>305</td>
<td>381</td>
<td>365</td>
</tr>
</tbody>
</table>

4.4 Determining Product Lot Sizes

Using the code which was written in GAMS software, lot sizes of Products 1 to 6 were optimized upon the proposed model in Appendix A. The obtained results are presented in Table 6 as well as the forecasted demands of the products. In Table 6, lot sizes are optimized during one working day.

Table 6. Capacity (Minute) after allocating correction capacity

<table>
<thead>
<tr>
<th>Products</th>
<th>Estimated demand</th>
<th>Period (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 7. Details of the received orders

<table>
<thead>
<tr>
<th>Order</th>
<th>Negotiable</th>
<th>Product type</th>
<th>Received period</th>
<th>Order Unit</th>
<th>Potential contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>2</td>
<td>3</td>
<td>15</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>1</td>
<td>4</td>
<td>20</td>
<td>210</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>3</td>
<td>5</td>
<td>20</td>
<td>225</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>5</td>
<td>7</td>
<td>20</td>
<td>180</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>6</td>
<td>8</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>170</td>
</tr>
</tbody>
</table>

4.5 Accepting/ Rejecting the Orders and Matching the In-press Units

Eight orders were received in the considered planning horizon, from which only one order is rejected. Details of the received orders and their relevant acceptance/ rejection results are presented in Table 7.

The first order was received in Period 3, which had no problem with the due date; hence, it is matched to Product type 1 at first. When Order 2 was received in Day 4, Order 1 has not been yet processed. After checking the due date and the unit availability for Order 2, the matching procedure was applied for both orders, whose result was to match Order 2 with Product type 1 and Order 1 with Product types 2 and 3. Since the amount of
Since the capacity was sufficient, the company negotiated with the customer solely on the new due date, and Order 6 was accepted, because the company agreed with the customer on the new due date. With respect to the units which were decided to be processed from the beginning of the line, changing costs of components were as the ones presented in Table 9. In order to calculate the numbers in Table 9, \( \alpha \) was considered 0.1 upon the experts’ comments.

The numbers in the parentheses show the cost of change for the stocked units. The results of order acceptance/ rejection and matching procedure are summarized in Table 10.

<table>
<thead>
<tr>
<th>Product type</th>
<th>Order</th>
<th>Accept/ reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40(60) 0 50(60)</td>
<td>Accept</td>
</tr>
<tr>
<td>2</td>
<td>0 60(80) 60(80)</td>
<td>Reject</td>
</tr>
<tr>
<td>3</td>
<td>50 70(85) 0</td>
<td>Accept</td>
</tr>
<tr>
<td>4</td>
<td>0 65(65) 70(70) 0</td>
<td>Reject</td>
</tr>
<tr>
<td>5</td>
<td>0 70(75) 70(75)</td>
<td>Accept</td>
</tr>
<tr>
<td>6</td>
<td>40(55) 0 60(70)</td>
<td>Accept</td>
</tr>
</tbody>
</table>

Moreover, the ratio of unmatched units at the end of the planning period to the total production is significantly reduced which was too essential for the company, since it directly affects costs of inventory. As the company adopted an MTF production system, on-time delivery ratio plays an important role in production and marketing perspectives. This ratio reveals firm’s flexibility in accepting diverse orders by coping market volatility and uncertainty. Also, market risks are better managed regarding product shortage or overstock. With respect to the production aspect, better on-time delivery ratio is a direct signal of manufacturing process improvement, resulting in the improved production characteristics, such as responsiveness, customization, and lead time. Overall, this is concluded that the firm captures higher level of customer satisfaction with direct impact on customer loyalty, and firm’s profitability and market share.

5 CONCLUSION AND FUTURE RESEARCH DIRECTIONS

A growing type of hybrid production systems is the MTF systems in which orders are generally matched with the in-process units of products. Having the MTF system is adopted several production planning and control issues arise, among which capacity coordination might be one of the most challenging ones. This paper addressed capacity coordination decision in the field of MTS production systems by proposing a framework which attempts to cope with the acceptance/ rejection decision and the matching procedure of the system. In this regard, the proposed framework includes four steps. Production value of each product is calculated using AHP method at the first step. The second step is related to correction capacity allocation. Then a mathematical programming model was developed so as to calculate product lot sizes. At the fourth step, acceptance/rejection of the receiving orders is decided. Also, a matching procedure is proposed, upon which the most suitable in-process units are assigned to the accepted orders to maximize net contribution of the system. Finally, results of application of the proposed framework in an industrial case study were reported to validate the
proposed framework. Upon the obtained results, the proposed framework enhanced on-time delivery ratio of the company and reduced ratio of the unmatched in-process units to the total production. The results improved the firm’s profitability and market share by enhancing level of customer loyalty.

In order to continue the research direction of this paper, suggestions are fivefold. First, outsourcing might be an assumption of the lot sizing model to make the model more practical. Also, proposing a mathematical model for determining best prices and due dates in the negotiation is another interesting suggestion. Third, developing a model for correction capacity allocation is another challenge of the MTF systems. Fourth, it is recommended to develop an inexact algorithm for the proposed assignment model in larger size problem instances. Finally, other optimization packages are suggested to tackle the developed models, such as CPLEX.

Appendix A. The proposed mathematical model for determining product lot sizes

The proposed model is based on the order forecasts, for following indices, parameters and variables are defined.

Indices:

\( i = 1, \ldots, n \) unit type
\( j = 1, \ldots, m \) production resource
\( k = 1, \ldots, K \) time
\( t = 1, \ldots, T \) time
\( R(i) \) set of required resources for unit type \( i \)

Parameters:

\( D_{ik} \) estimated demand of unit type \( i \) with due date \( k \)
\( Regst_{ij} \) setup time of unit type \( i \) on resource \( j \) in regular time
\( OTst_{ij} \) setup time of unit type \( i \) on resource \( j \) in overtime
\( Regsc_{ij} \) setup cost of unit type \( i \) on resource \( j \) in overtime
\( OTsc_{ij} \) setup cost of unit type \( i \) on resource \( j \) in regular time
\( h_i \) holding cost of unit of product type \( i \) in a planning period
\( b_i \) backlog cost of unit of product type \( i \) in a planning period
\( Regc_{ij} \) production cost of unit type \( i \) on resource \( j \) in regular time
\( OTc_{ij} \) production cost of unit type \( i \) on resource \( j \) in overtime
\( Pval_{ij} \) production value of unit type \( i \)
\( REGCAP_{ij} \) regular time capacity of resource \( j \) in planning period \( t \)
\( OTCAP_{ij} \) overtime capacity of resource \( j \) in planning period \( t \)
\( RC_{ij} \) the allocated time of resource \( j \) to the unit of product type \( i \)
\( CAP \) total storage capacity

Variables:

\( x_{ik} \) lot size of unit type \( i \) in period \( t \) with due date \( k \) in regular time
\( y_{ik} \) lot size of unit type \( i \) in period \( t \) with due date \( k \) in overtime
\( s_{ij} \) binary; setup of unit type \( i \) on resource \( j \) in regular time \( t \)
\( t_{ij} \) binary; setup of unit type \( i \) on resource \( j \) in overtime \( t \)
\( Regres_{ij} \) resource \( j \) available time in regular time \( t \)
\( OTres_{ij} \) resource \( j \) available time in overtime \( t \)

Proposed model:

\[
\begin{align*}
\text{Min} & \quad \left[ RC_{ij} \times \sum_{t} \sum_{k} y_{ik} \right] + \\
& \quad \left[ OTc_{ij} \times \sum_{t} \sum_{k} s_{ij} \right] + \\
& \quad \left[ OTsc_{ij} \times \sum_{t} \sum_{k} t_{ij} \right] \\
& \quad + \sum_{i} \sum_{k} \sum_{j} \left( k-t \right) \left( x_{ik} + y_{ik} \right) + \\
& \quad \sum_{i} \left( h_i \times \sum_{k} \max \left\{ 0, D_{it} - \sum_{j} \left( x_{ik} + y_{ik} \right) \right\} \right) \\
& \quad + \sum_{i} \sum_{j} \left( \sum_{k} \left( x_{ik} + y_{ik} \right) \right) \\
& \quad + \sum_{j} \left( RC_{ij} \times \sum_{k} \left( x_{ik} + y_{ik} \right) \right) + \\
& \quad \sum_{i} \left( \sum_{j} \left( \sum_{k} \left( \sum_{t} \left( Re gsc_{ij} \times \sum_{i} \sum_{k} s_{ij} \right) + OTst_{ij} \times t_{ij} \right) \right) \right) e \in R(i), t \quad (A-1)
\end{align*}
\]

Acknowledgment

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Objective function (A-1) seeks to minimize sum of the operating costs (regular time and overtime), setup costs, holding and backlog costs, while production values of products in regular time is maximized. Constraints (A-2) consider available capacities of resources in each planning period. Constraints (A-3) and (A-4) are related to the setups in regular and over time, respectively; while maximum available capacities are taken into account in Constraints (A-5) and (A-6). Constraints (A-7) represent available storage capacity for the products. Finally, Constraints (A-8) define variables of the proposed model.

Appendix B. The proposed matching mathematical model
Having some orders accepted, it is required to match the accepted orders with the in-process units. As mentioned in Section 3.4.4, the accepted orders are matched with either unmatched units or the previously matched ones which have not yet processed. Followings describe the developed model for the matching process.

Indices:
- \( k \): unit
- \( l \): order
- \( q = 1, \ldots, NP \): number of the products of order \( l \)
- \( S(t) \): set of unmatched units and the units previously matched but not processed yet
- \( D(t) \): set of new orders
- \( O(t) \): stock units and the ones which are completed at current period

Parameters:
- \( s_{iq} \): Net contribution of assigning unit
- \( U_i \): to order \( V_i \) with size \( q \)

Variables:
- \( x_{iq} \): Binary; assignment of unit \( k \) to \( q^{th} \) element of order \( l \)

The objective function seeks to maximize the total net contribution, \( s_{iq} = R \cdot M_i - \Delta(u_i, v_{iq}) + \alpha \cdot h_l \), where \( R \times M_i \) is the potential contribution of order \( l \), \( \alpha \) is a fixed percentage, and \( M_i \) represents the market value of order \( l \). Moreover, \( \Delta(u_i, v_{iq}) \) shows the cost of changing unit \( k \) to desired product confirming the \( q^{th} \) element of order \( l \). In order to match stock units, \( O(t) \), to the orders, the value of \( \alpha \cdot h_l \) is considered to increase their desirability (\( \alpha \) is determined by experts and \( h_l \) represents holding cost of one unit of the product to be matched with order \( l \)). Additionally, Constraints (B-2) are used to permit each unit \( k \) to be assigned to the \( q^{th} \) element of order \( l \). Constraints (B-3) ensure all elements of each order are matched with the units. Finally, Constraints (B-5) define binary variables \( x_{iq} \).

Appendix C. The proposed matching mathematical model for rematching the unmatched orders with the in-process units
Upon the model in Appendix B, if it is decided to match the received order with the previously matched units, the following model is used to rematch the unmatched order with some new in-process units.

The explanation of the model is similar to the model in Appendix B. \( D'(t) \) is set of previously accepted orders which are unmatched now; \( S'(t) \) represents set of unmatched units; and \( mp \) shows the number of components of order \( l \) that became unmatched after using model of Appendix B.
References